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PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

INTERACTION OF A TURBULENT BOUNDARY LAYER

WITH A STEP AT M = 3

C.E. Kepler and S.M. Bogdonoff

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ACKNOWLEDGEMENT

The present study is part of a program of theoretical and experimental research on viscous effects in supersonic flow being conducted by the Gas Dynamics Laboratory, Forrestal Research Center, Princeton University. This research is sponsored jointly by the Office of Naval Research (U.S.N.), Mechanics Branch and by the Office of Scientific Research (U.S.A.F.) under Contract Number N6-onr-270, Task Order No. 6, Project Number NR-061-049.

Mr. C.E. Kepler is now with the Research Department of United Aircraft Corporation of Hartford, Connecticut.

SUMMARY

An experimental investigation of the flow over a two-dimensional step was carried out at a Mach number of 2.92. The separation of a turbulent boundary layer and the associated shock wave pattern were studied as the step height was varied from 1/3 to 2 times the boundary layer thickness. The interaction was observed by Schlieren and shadowgraph techniques supplementing the wall static pressure surveys and detailed total head surveys through interaction. Reverse flow regions were investigated by using a tiny total head tube which would face downstream as well as upstream.

For all steps tested, separation was detected at a wall static pressure ratio of 2.1. After the separation point the pressure continued to rise, but at a slower rate, to a maximum value which assumed a constant value for the steps which were higher than the boundary layer. For these step heights, the front parts of the interaction were identical. The pressure distribution, the pressure ratio, and location of the separation point, were identical and duplicated the results obtained in the studies of a strong incident shock interacting with a turbulent boundary layer. The occurrence of separation and the initial region of separated flow (covering a distance of 6 to 8 boundary layer thicknesses) appears to be independent of the cause of separation in spite of the large differences in the flow downstream of this region.

INTRODUCTION

In recent years, many investigations have been directed toward the study of the interaction of shock waves with boundary layers. At present, some theoretical analysis (references 1-4) and a considerable body of experimental data (references 5-10) are available for the cases of both the laminar and turbulent boundary layers. A recent study conducted by the Gas Dynamics Laboratory of the James Forrestal Research Center, Princeton University (reference 11) explored the interaction of varying strength shocks with a turbulent boundary layer. It was found that for strong incident shocks, the interaction spread a considerable distance both upstream and downstream of the theoretical impingement point of the incident shock. Although the extent of the forward propagation of the interaction was found to be a function of the incident shock strength, it seemed as if the occurrence of separation and the initial region of the separated flow should be independent of shock strength or method of causing the separation. Hence, it was decided to explore in more detail the flow in that region. Recent work by Donaldson and Lange (reference 12), and Beastall and Eggink (reference 13) using a step on the wall to produce separation, prompted a similar approach for studying the front part of the interaction. Donaldson and Lange found the phenomena to be independent of step height (for steps higher than the boundary layer thickness). The aforementioned studies of the shock wave boundary layer interaction found a similar condition for the front part of the interaction when the separated region was large. However, an appreciable change was noted when the separated region was small. In an attempt to simulate the varying size of the separated region, steps varying in

height from 1/3 to 2 boundary layer thicknesses were used. The results presented herein have been restricted to a study at a Mach number of 2.92 for one turbulent boundary layer. Only the step height was varied.

Detailed investigation of the interaction was made by 1) measuring the static pressure distribution on the solid walls, 2) making total head surveys through the interaction, and 3) using optical techniques to obtain photographs of the flow. This work was carried out under the joint sponsorship of the Office of Naval Research, Mechanics Branch, and the Office of Scientific Research.

NOMENCLATURE

x - distance measured along tunnel wall from face of step - inches

y - distance measured perpendicular to wall - inches

h - step height - inches

P - local static pressure

P_1 - free stream static pressure

P_o - chamber pressure

P_t - total head pressure

M - Mach number

δ - boundary layer thickness - inches

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

The experiments were performed in the Princeton University pilot supersonic wind tunnel (reference 14) at a Mach number of approximately 2.92. The wind tunnel is the "blow down" variety utilizing air stored at 3,000 psi in tanks of a total capacity of 170 cubic feet. A regulator between the tanks and tunnel permits operation at any desired stagnation pressure between 75 psi and 300 psi; but for the tests herein reported it was operated at a pressure level of about 105 psi. Running times were of the order of five minutes with the Mach 3 nozzle which has a test section 2 inches wide and $2\frac{1}{2}$ inches high.

The fully turbulent boundary layer on the flat section of the tunnel wall was utilized for the experiments. The undisturbed boundary layer thickness was about .17 inches. The interaction phenomena was caused by placing full span steps (to within .010" of either side wall) on the tunnel wall. These steps varied in height from .050" to .350" at intervals of .050". They were mounted on a supported frame which was driven by a micrometer (see figures 1 and 2) enabling longitudinal positioning accurate to within .005". At the front and bottom of each step a .030" balsa wood strip was inset to act as a seal as well as a bearing surface to prevent gouging of the tunnel wall as the step was moved.

The static pressure on the wall was measured by a .030" orifice on the tunnel centerline. All wall static pressure distributions presented were made using this single orifice as the interaction was passed over it. Thus, errors in using numerous orifices were eliminated and data points could be spaced as closely as desired. Additional spanwise static

pressure orifices were used to check the two-dimensionality of the interaction. These were located 3/8", 1/2", 5/8", and 3/4" off centerline but at the same station as the main orifice. All data were checked using these spanwise static pressure taps and found to be two-dimensional.

Total pressure surveys were made parallel and normal to the tunnel wall employing a total head tube .25" long which was constructed of .024" O.D. stainless steel tubing flattened at the end and honed on the bottom surface to allow a close approach to the wall. The orifice was .004" high with a wall thickness of .003". Thus, readings to within .005" of the surface were obtainable. The total head probe was set in an insulated mount so an electrical contact could determine when the tube was just touching the wall surface. A micrometer drive made possible displacement perpendicular to the wall, accurate to within .001". For every survey the "just touching" position was established with the tunnel running, since presetting of the probe might be erroneous due to deflection because of the air pressure during running or starting.

The static pressure on the face of the step was checked only for the .300" high step. Five orifices were drilled at heights of .050", .100", .150", .200", and .250" near the centerline. It is estimated that all pressure measurements are accurate to within 2%.

Optical techniques supplementing the pressure measurements were used to study the phenomena. The conventional skewed biparabolic mirror Schlieren system was used and adapted for shadowgraph pictures as well. The light source was a high pressure spark resulting in exposures of the order of a microsecond. In addition, color Schlieren photographs were also taken using the spark source (reference 11). Although the color Schlieren

photographs present a more comprehensive picture than the conventional black and white Schlieren pictures, the difficulty of their reproduction prohibited their presentation in this paper.

The steadiness of the flow was checked by taking high speed Schlieren motion pictures with a "Fastax" camera operating at about 8,000 frames per second. An examination of these photographs showed very slight oscillations of the shock, Its movement was less than 1/10 of the boundary layer thickness, i.e., less than .02". The rest of the phenomena appears completely steady. Because of the type of pressure pickups and the very high frequency of these small oscillations, this phenomena was not indicated in the pressure measurements. This examination was carried out only for the .25" step.

RESULTS AND DISCUSSION

The flow of a turbulent boundary layer over a step was first examined by taking Schlieren and shadowgraph photographs. Figures 3 and 4 are pictures of the interaction as the step height was varied. No quantitative data obtained from these pictures is presented in this report. Measurements taken, however, showed shock angles slightly greater than those obtained by Donaldson and Lange. This discrepancy may be due, in part, to the position where the shock angle was measured. For a given interaction the shock angle varied, it was steeper further away from the wall (where the measurements were taken) than at the boundary layer edge. Evidently a compression region follows the initial shock and these waves coalesce further out strengthening the shock.

This was even more clearly seen from the color Schlieren photographs. In addition, a trend toward weaker shocks was noted as the step height decreased to less than the boundary layer thickness.

Measurements of the static pressure distribution along the wall substantiated the observation from the photographs that the pressure was varying appreciably behind the initial shock. In figures 5 through 11 are presented the pressure curves, for the various steps used. Figure 12 is a composite of the forementioned data without the experimental points. The zero reference was the face of the step and distances measured upstream are considered negative. All the curves exhibit a steep initial rise at the position where the "shock", as seen from the picture, penetrated deep into the boundary layer. Downstream of this the pressure on the wall continued to increase for some distance with a reduced gradient. For the high steps the pressure continued to rise over a distance of about 7 boundary layer thicknesses. All cases exhibited an inflection in the pressure curve and another steep rise immediately in front of the step. For the large steps a slight reduction in pressure preceeded this rise. This phenomena was probably caused by a strong vortex in the corner. This prompted a check of the static pressure on the face of the step and the examination was carried out for the .30" step. The results presented in Figure 13 show high pressures at both the top and bottom corners indicating a stagnation region at both places. Although a check with high speed motion pictures found the flow to be very steady, and over most of the interaction region pressure measurements were quite repeatable and without oscillations, the measurements on the wall near the corner were found to vary somewhat during a

test. Evidently the strength of the vortex was quite critical to slight oscillation in the tunnel flow or to tunnel operating condition. For this reason the detailed studies, to be discussed later, were not conducted near the face of th step. The consistency of the data taken over the front part of the interaction reveals that the flow in this region is either independent of or very insensitive to the flow near the face of the step.

Further examination of the wall static pressure curves reveals that the front part of the interaction changed for steps equal to or less than the height of the boundary layer. The initial pressure rise was the steepest for the smallest step tested. With increasing step height, the pressure rise became less rapid tending toward an asymtotic value for larger steps. All the pressure curves exhibited a maximum, the value of which increased as the step heights increased, again tending toward a constant value for the high steps. It should be noted that for the three highest steps (h = .25", .30", .35") the front part of the pressure curves are identical in all respects.

Studies of the flow near the wall were carried out by surveying parallel to the wall with a total head tube positioned at 0.010" from the wall (a height of approximately 1/16 of the boundary layer thickness). These measured total pressures, the corresponding measured wall static pressures, and the conventional pitot-static relationships were used to obtain the Mach number distributions shown in figures 14 through 20. The interaction region for the .050" step was too small to survey. For the other interactions, the curves are all similar, indicating a rapid deceleration of the flow near the wall. The flow is completely stopped

within three boundary layer thicknesses, the deceleration being slightly more rapid for the cases of the small step (i.e. h = .10" and .15"). It is interesting to note that these curves duplicate exactly the results of similar surveys made in the upstream region of the shock wave boundary layer interaction studies (reference 11).

A detailed study was carried out for the flow over the .30" step as representative of all interactions caused by steps higher than the boundary layer. Total head surveys were made normal to the wall at various stations through the interaction. A schematic drawing of the interaction in juxtaposition with the wall static pressure distribution is shown in figure 21. In figure 22 are presented the total head profiles through the boundary layer. To obtain more detail of the flow in the separated region, particularly the determination of the reverse flows and zero velocity contour, additional surveys were made with the total head tube facing downstream. These profiles are presented in figure 23 with the corresponding data of figure 22.

The undisturbed boundary layer profile is obtained from the survey at station -1.7" (figure 22). Here the boundary layer thickness is about .17", the displacement thickness .0489", and the momentum thickness .0090". Over the distance spanned in the next four surveys (x = -1.6", -1.5", -1.4", -1.3") the wall static pressure has nearly doubled, but the flow has not yet separated. These profiles show the essential mechanism causing separation, i.e., rapid deceleration of the inner region of the boundary layer. The remaining profiles show the growth of the separated region.

Examination of figure 23 for stations x = -1.3 and x = -1.2 shows that separation occurs between these two stations. No reverse flow is indicated at x = -1.3 while a region of reverse flow out to y = .025" is indicated at station x = -1.2. The reverse flow is indicated by a lower total head reading when the total head tube is facing upstream as compared to the reading when it is facing downstream. This is caused by a "base pressure" effect of the air flowing over a body with a blunt base. The correct total head profile must therefore always be the one indicating the highest readings, the direction of the flow is indicated by which tube reads the highest at that station, and the zero velocity line is indicated by the same reading on both the upstream and downstream pointing total head tubes. After the onset of separation, the zero velocity contour was inclined at an average angle of about 8° with the wall. The experiment indicated that the angle increased with distance downstream. The maximum Mach number in the reverse flow region increased downstream to a value of about 0.3 at the last station surveyed.

Further examination of the results from the detailed study of the .30" step reveals the following information:

1) The maximum wall pressure gradient is realized between station -1.6 and -1.5. Here the "compression waves" are entirely within the boundary layer, the total head profiles exhibit no bumps indicative of discontinuities caused by shocks. The wall pressure has increased about 50% while the pressure at the edge of the boundary layer is still at the free stream value. Thus, it is obvious that in this region the pressure gradients normal to the wall are of the same order of magnitude as the gradients along the wall.

2) For the other stations surveyed, the "shock", as evidenced from Schlieren and shadow photographs, is outside of the boundary layer. The total head curves reach a maximum value before penetrating the shock, any pressure discontinuities are smeared by the introduction of this physical body (total head tube) into the flow. Calculation of shock strength from the measured total head surveys was felt to be justified only at stations -0.8" and -0.6". The respective shock pressure ratios obtained were 2.36 and 2.42. To obtain an idea of the pressure at the edge of the boundary layer, isentropic relationships were used in conjunction with the above mentioned shock pressure ratios and the measured total head variation between the shock and the edge of the boundary layer. For these two cases, which are more than 5 boundary layer thicknesses downstream from the front of the interaction, the pressure variation through the viscous region was found to be less than 4%.

Significant data abstracted from all the tests was combined in figures 24, 25 and 26, and plotted as a function of the one parameter that was varied, step height. A significant trend toward constant values can be noted for all the data when the step was larger than the boundary layer. Evidently the flow phenomena in the front part of the interaction is independent of the step height if the step is sufficiently high. One would expect that as the step was increased in height beyond 2 boundary layer thicknesses only the scale of the interaction would change. This is the realm of step heights used in the experiments conducted by Donaldson and Lange. For steps of the order of or less than a boundary layer thickness, the phenomena change, however. As the step height was decreased, the pressure rise was more rapid - the maximum pressure gradient

along the wall lowered over the range tested - the maximum pressure associated with the front part of the interaction decreased, and the distance to separation decreased slightly. Within the accuracy of the measurements, the pressure ratio for separation did not vary over the range tested. For the smallest step placed in the flow, the maximum pressure ratio was slightly greater than the pressure ratio for separation. For an even smaller step, it might be expected that the maximum pressure ratio would be <u>less</u> than the pressure ratio required for separation and a viscous region, without separation, may be the phenomena.

Shock wave turbulent boundary layer interaction studies (reference 11) conducted at Princeton University explored the effect of varying the incident shock strength. For very strong shocks there was a considerable propagation forward of the theoretical impingement point of the shock with the wall. For these cases, the flow phenomena associated with the front part of the interaction were postulated to be independent of the incident shock strength. The results presented in this report, concerning the front part of the interaction caused by the step, duplicate very closely the results obtained for the front part of the strong shock wave boundary layer interaction. Within experimental accuracies, the distance to separation and the pressure ratio required for separation are the same. For comparison, the wall static pressure plots for both the strong shock wave boundary layer interaction and the interaction of the .30" step are superimposed in figure 27. The front parts of both interactions are shown to be quite similar.

This similarity occurs even though the method of causing separation is quite different. As shown by the pressure distribution on the face

of the step (figure 13), there are very strong normal pressure gradients in the region close to the step. A quite strong vortex must be located in this region. Neither the vortex nor the strong normal gradient have been found in the shock wave boundary layer interaction studies. The occurrence of separation and the initial portion of the separated region (covering approximately 6 to 8 boundary layer thicknesses) appear, therefore, to be completely independent of the phenomena occurring downstream.

CONCLUSIONS

From the studies of the interaction caused by the flow of a turbulent boundary layer over a step in the wall, the following conclusions were reached:

1) For step heights greater than the boundary layer thickness, the flow phenomena associated with the front of the interaction are constant. Increasing the step height changes only the scale of the interaction.

2) For step heights less than the boundary layer thickness, the phenomena changes with step height. The pressure rise becomes more rapid and maximum pressure obtained decreases as the step height decreases.

3) For steps higher than a third of the boundary layer thickness,the flow separated and reverse flow was detected. The pressure ratio at the separation point is constant at a value of 2.1. The flow is characterized by a rapid deceleration of the inner regions of the boundary layer, separation occurring within two to three boundary layer thicknesses. For smaller steps, the maximum pressure appears to be assuming values less than the pressure required for separation. A viscous deceleration probably characterized the interaction and the flow may not separate for steps smaller than those tested herein.

4) The flow phenomena associated with the separation of a turbulent boundary layer and the initial growth of the separated region are the same for the interactions caused by a strong shock impinging upon the boundary layer and a step placed in the boundary layer in spite of the considerable differences in the flows downstream of these regions.

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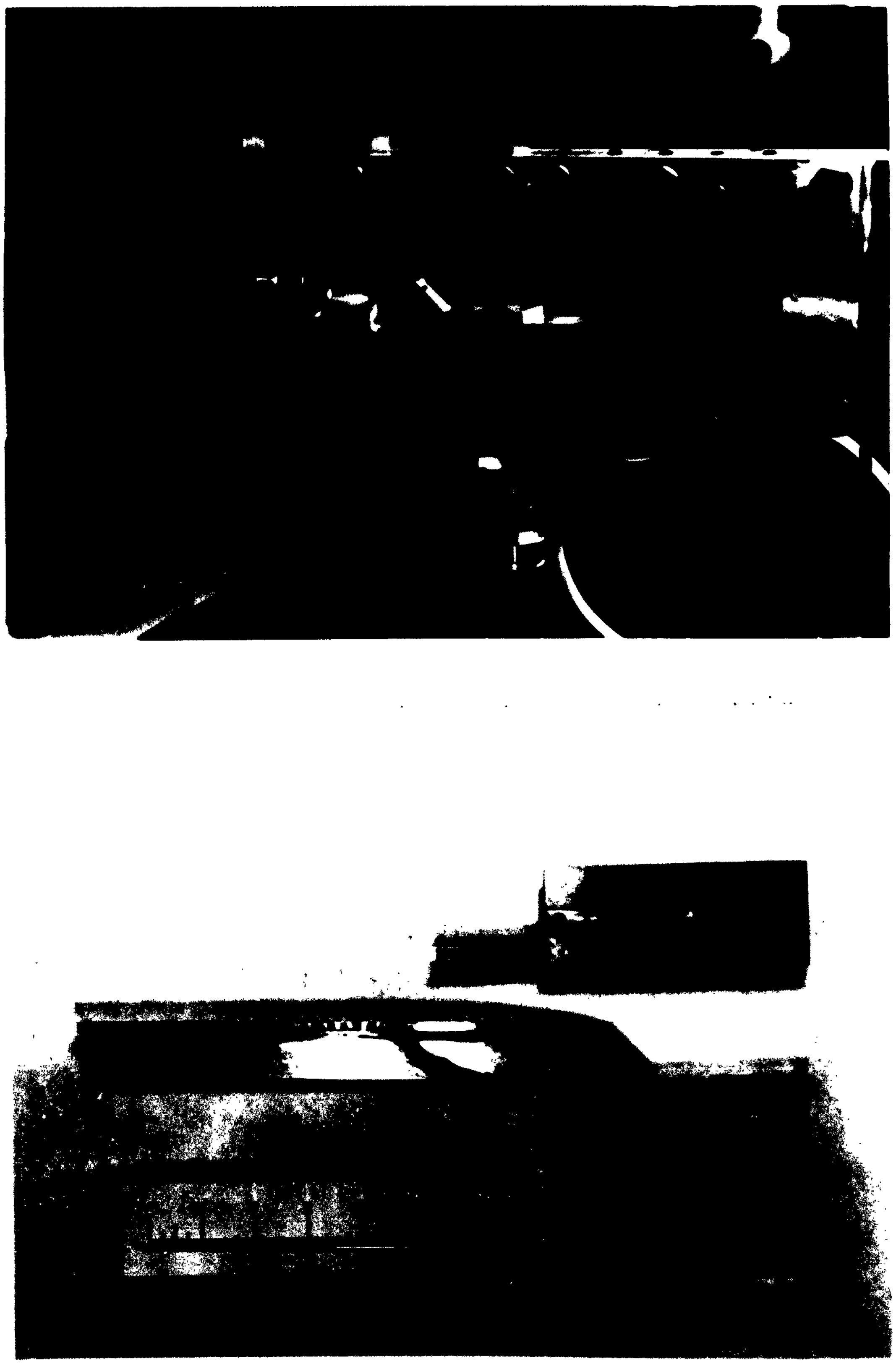


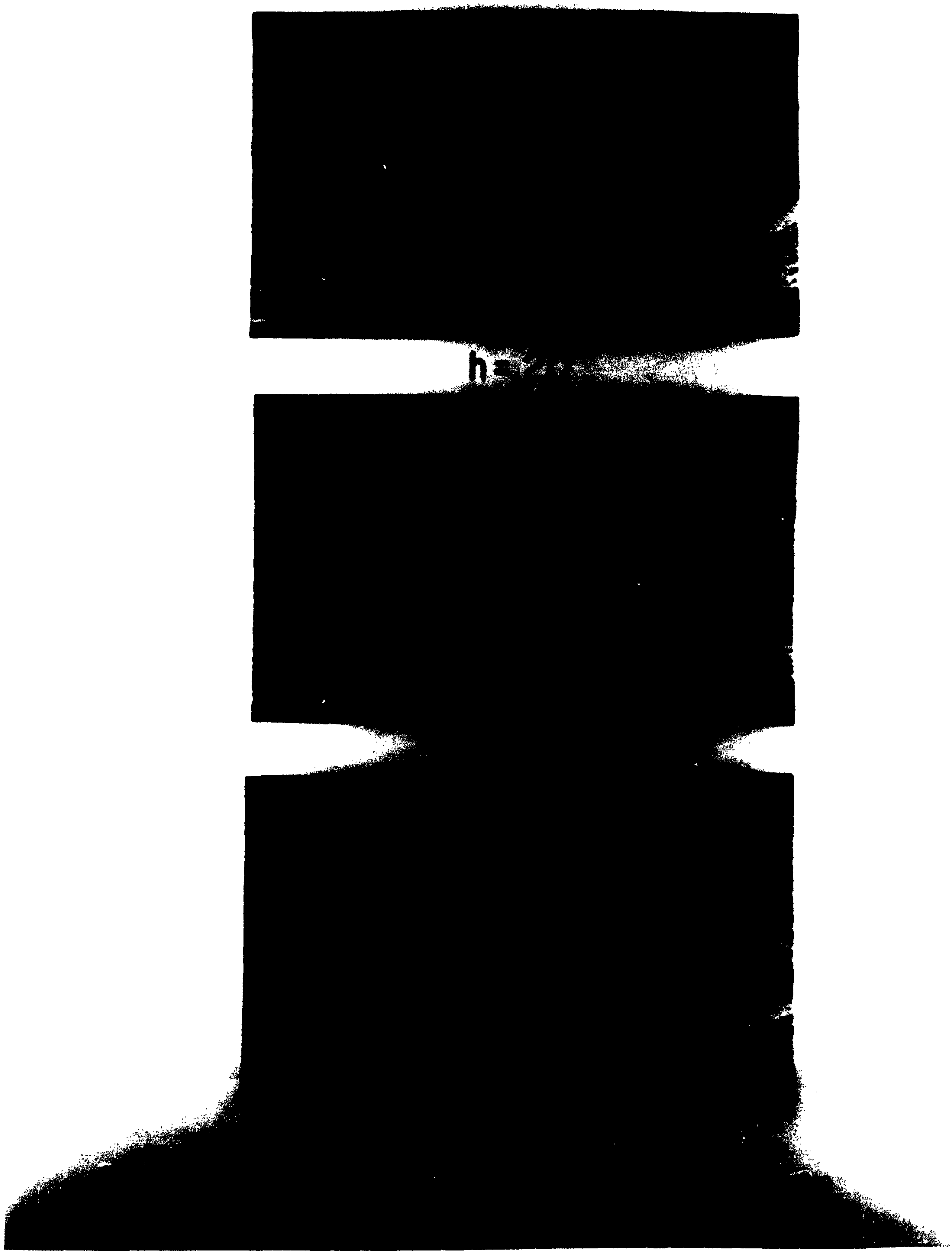
Figure 2 Total Head Probe, the Various Steps Used, and Their Mounting Mechanism

h = .05"

h = .10"

h = .15"

Figure 3 Optical Studies of Turbulent Boundary Layer Flow [illegible]
In Wall Schlieren Photographs (Horizontal Cut-off)


h=

h = .35"

Figure ... Concluded ... Schlieren Photographs (horizontal slit— ...

h = .05"

... Flow Over Step in

h =.10"

h=.15"

h=

Figure [illegible]

h=.25"

h=.30"

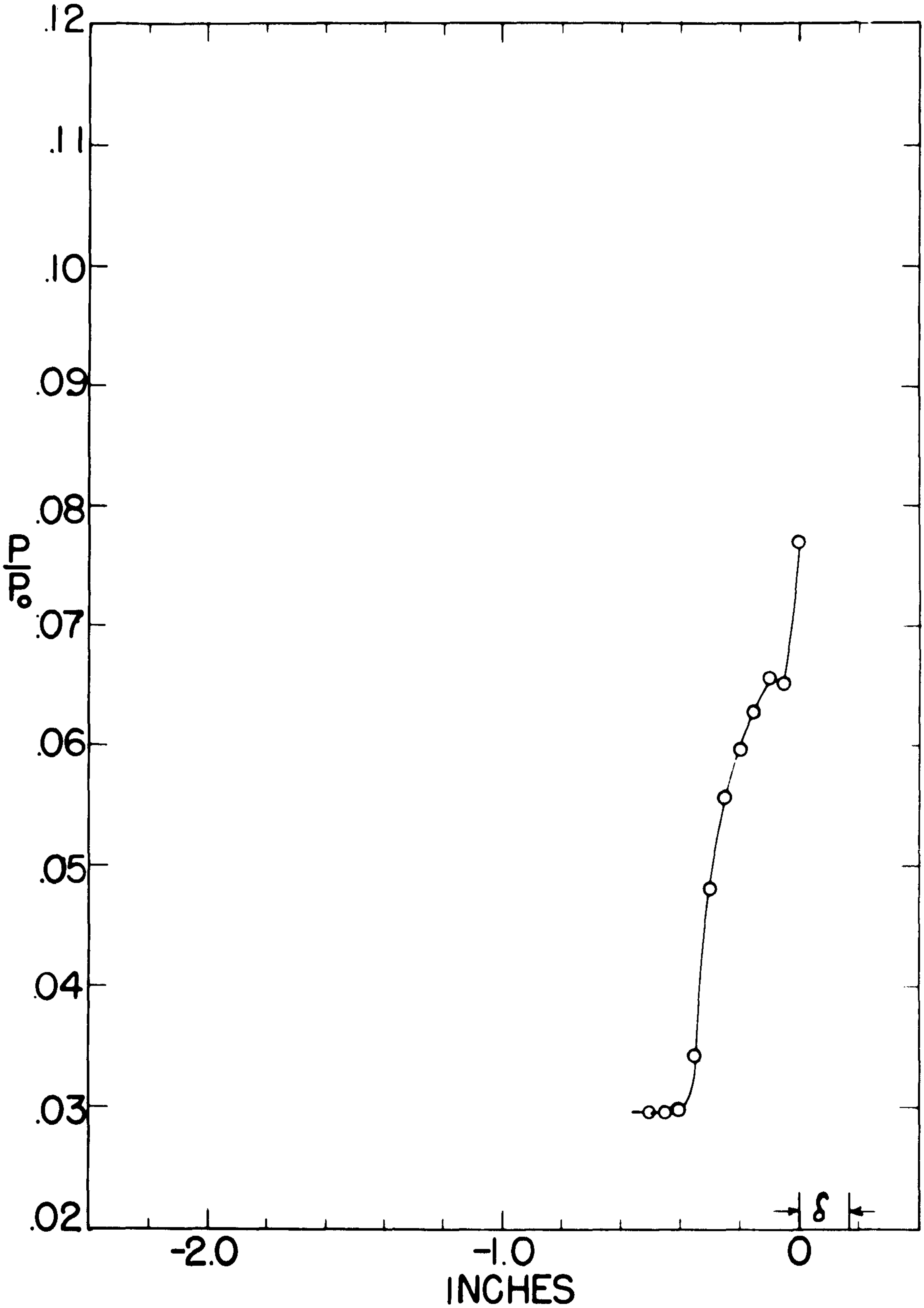


Figure 5   Wall Static Pressure Distribution for .05" Step

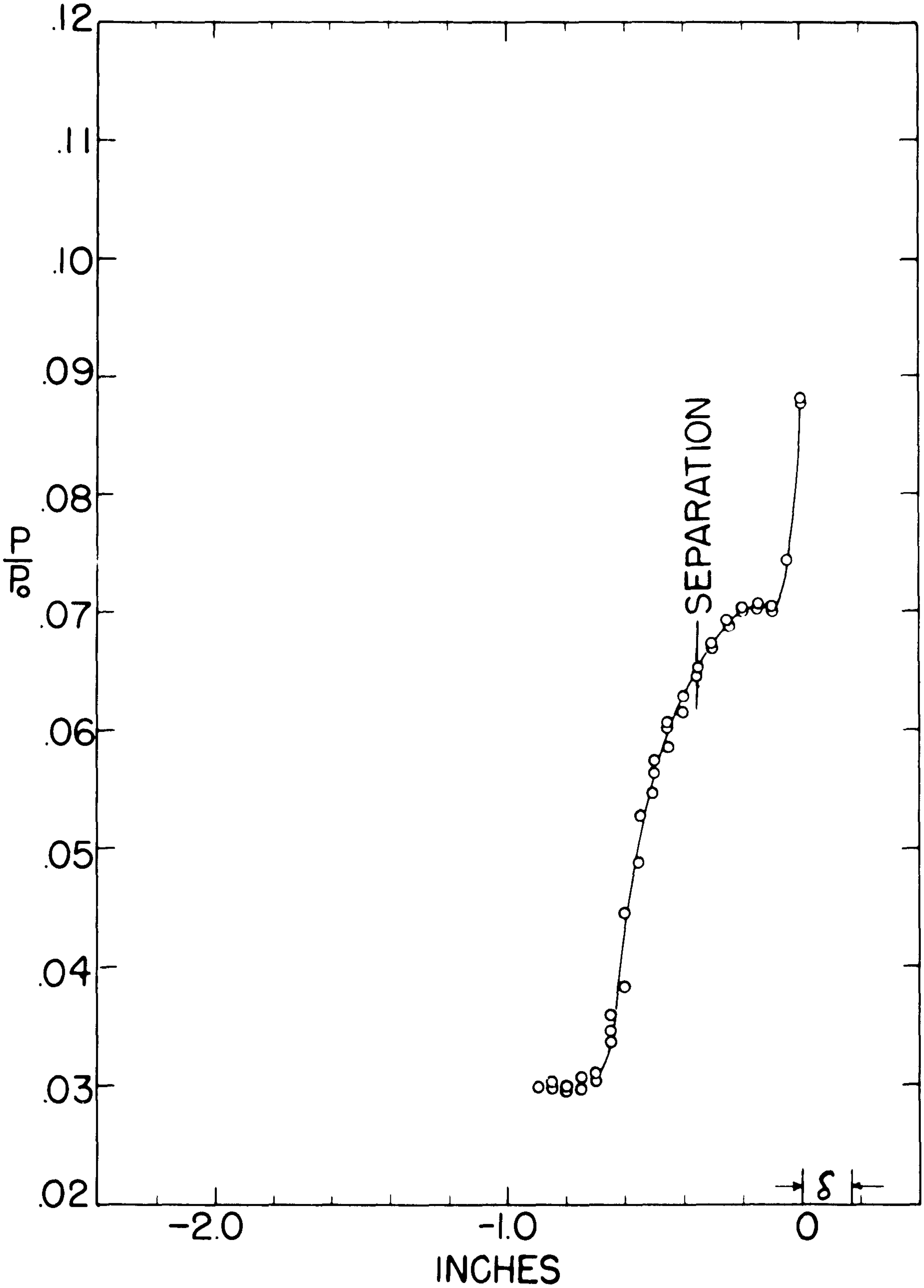


Figure 6 Wall Static Pressure Distribution for .10" Step

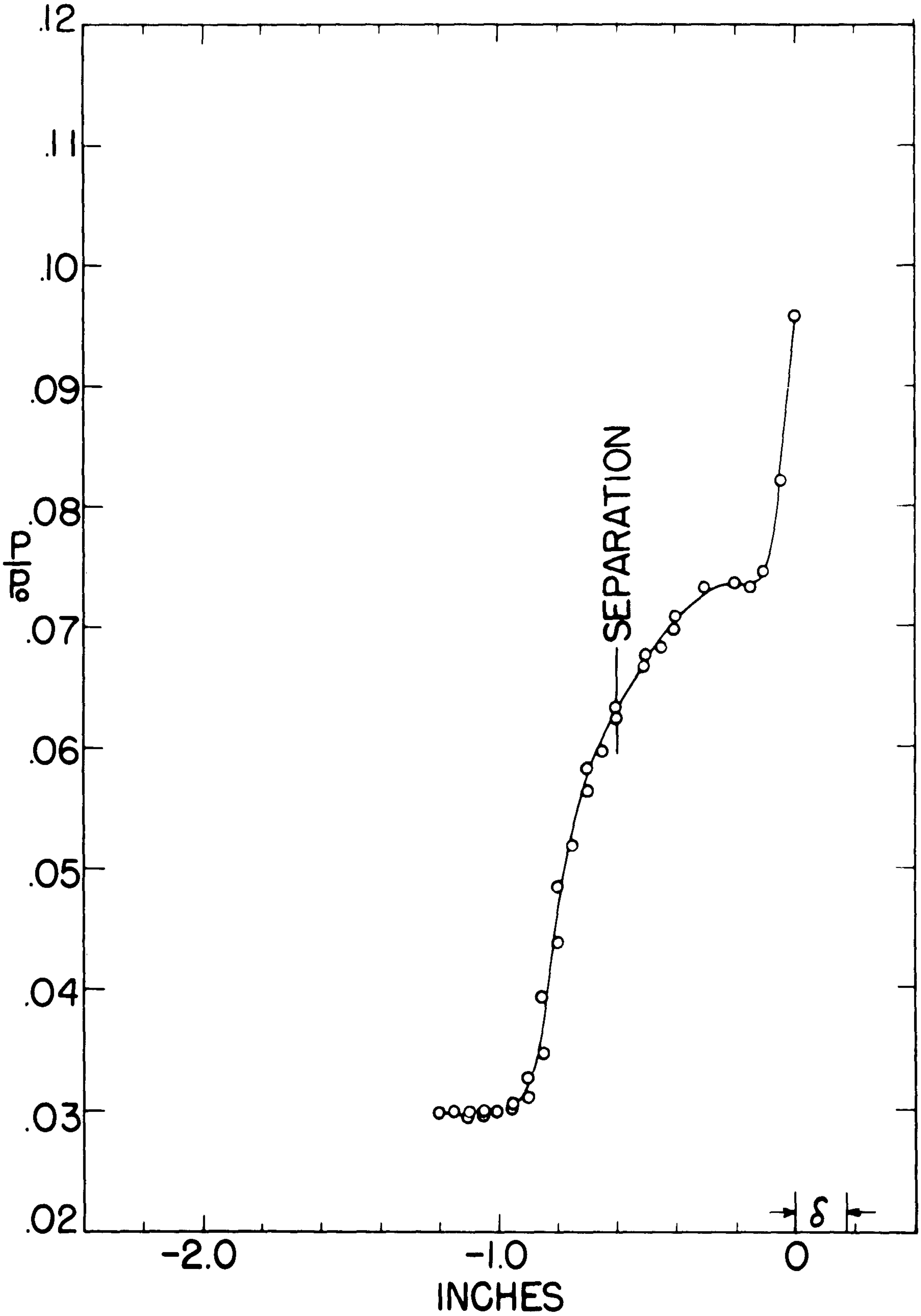


Figure 7 Wall Static Pressure Distribution for .15" Step

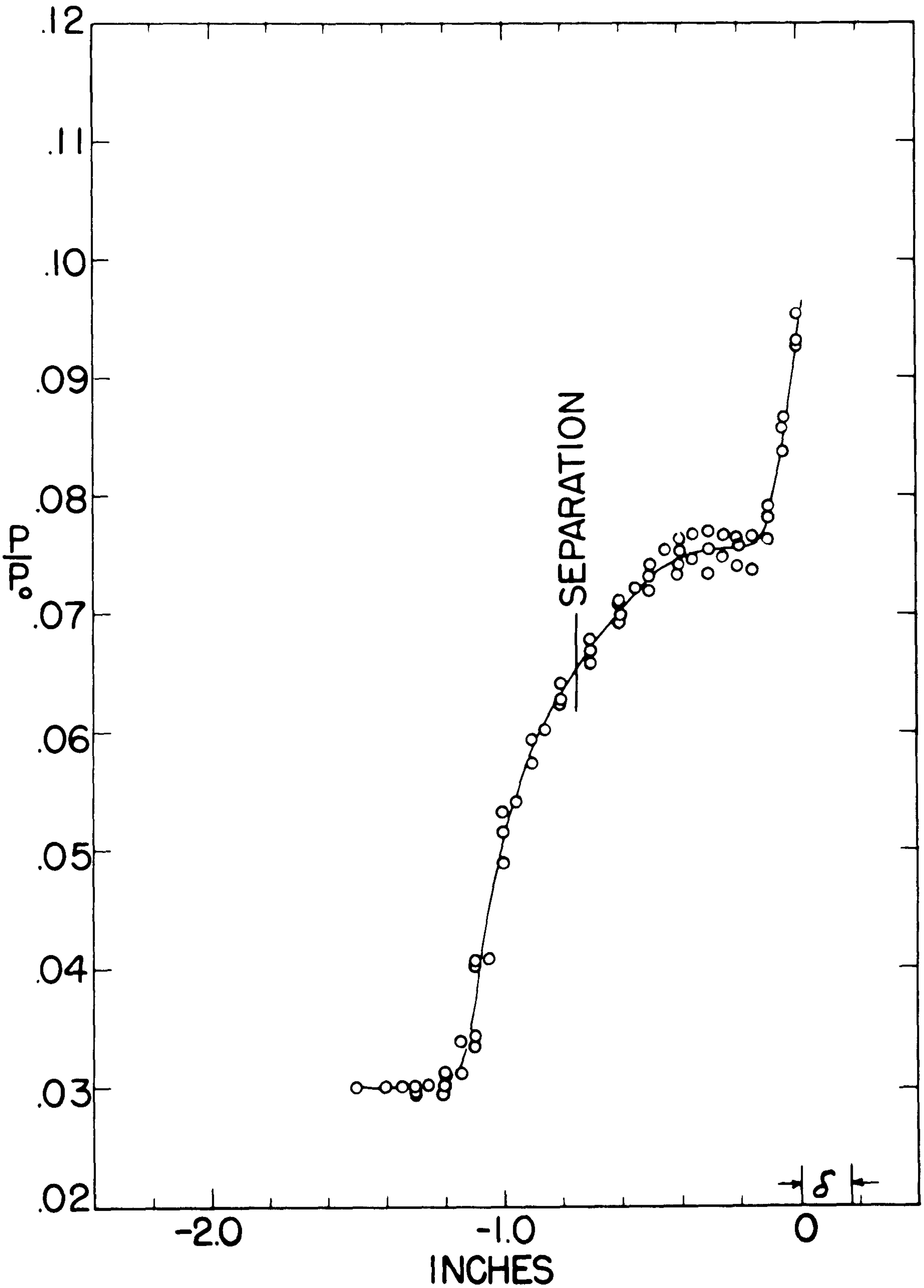


Figure 8 Wall Static Pressure Distribution for .20" Step

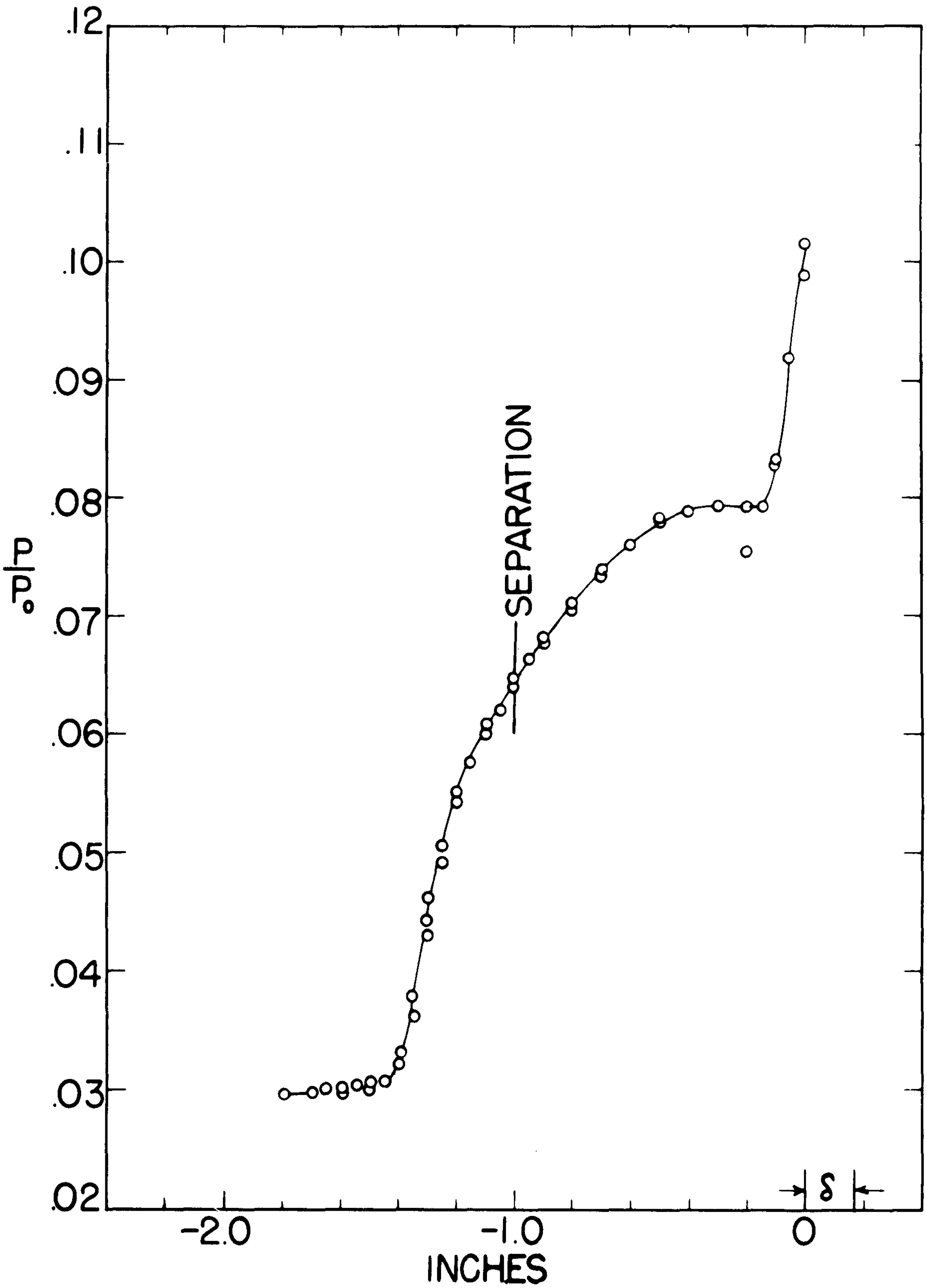


Figure 9 Wall Static Pressure Distribution for .25" Step

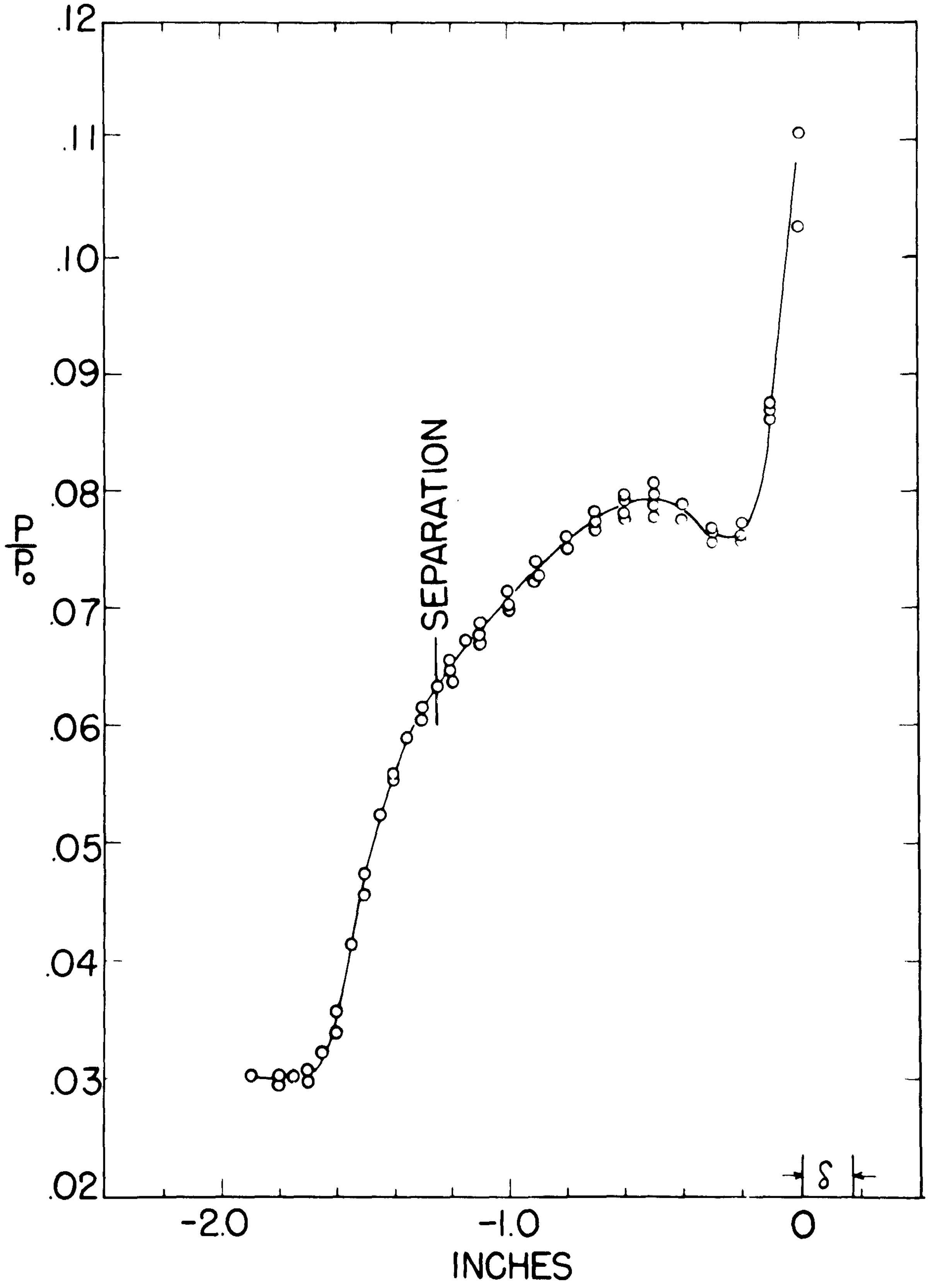


Figure 10 Wall Static Pressure Distribution for .30" Step

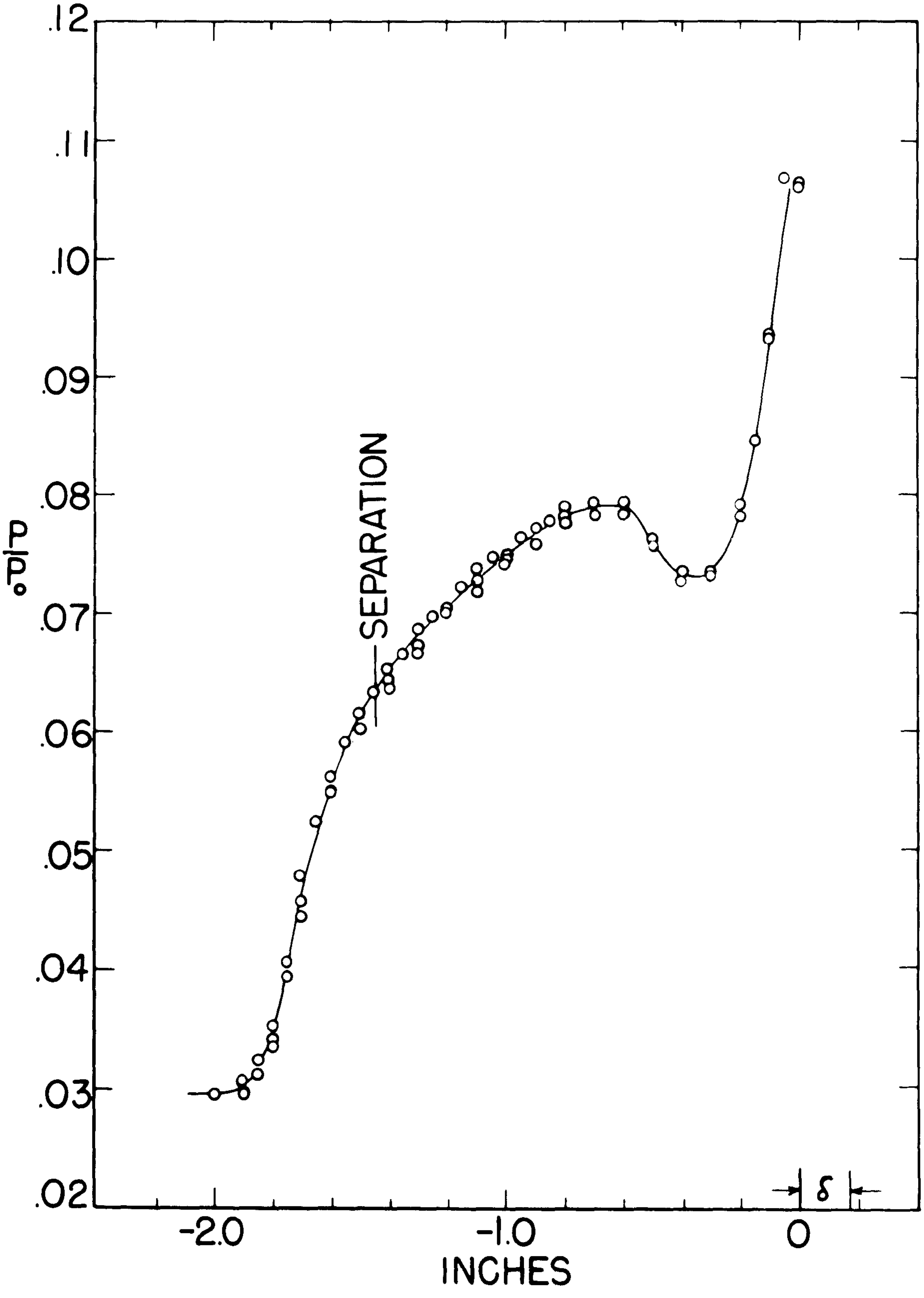


Figure 11 Wall Static Pressure Distribution for .35" Step

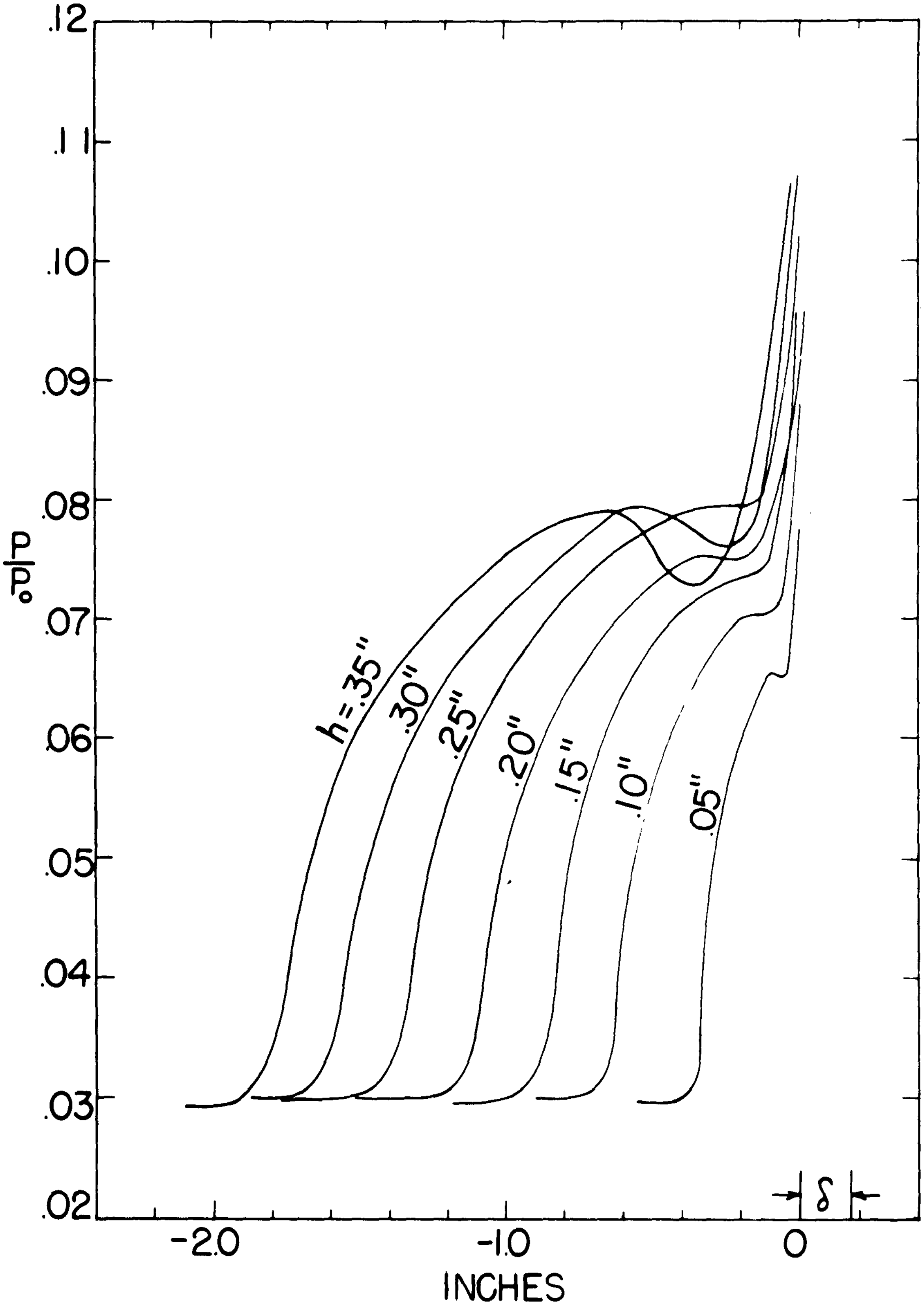


Figure 12 Composite of Wall Static Pressure Distributions

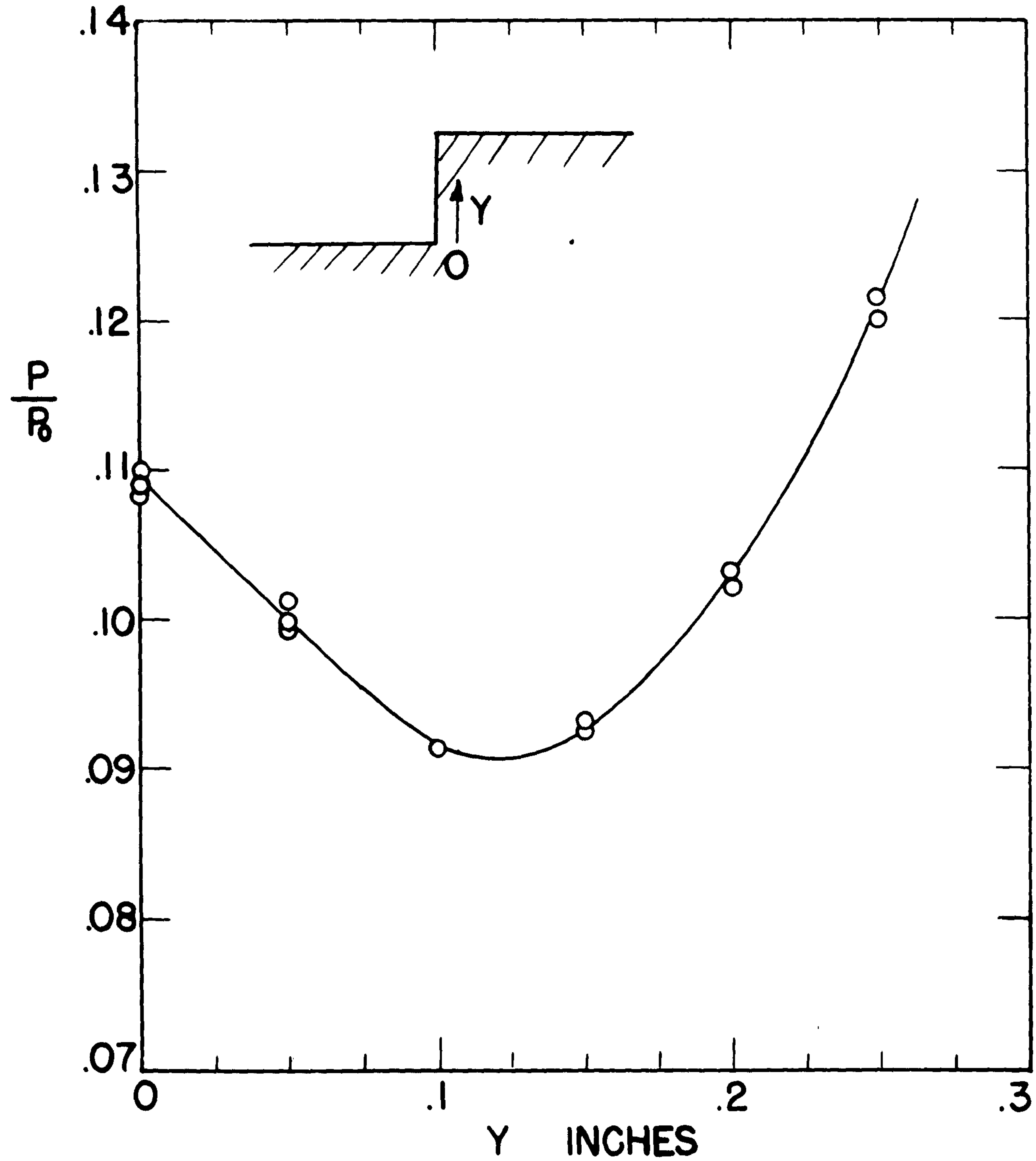


Figure 13 Static Pressure Distribution on Face of .30" Step

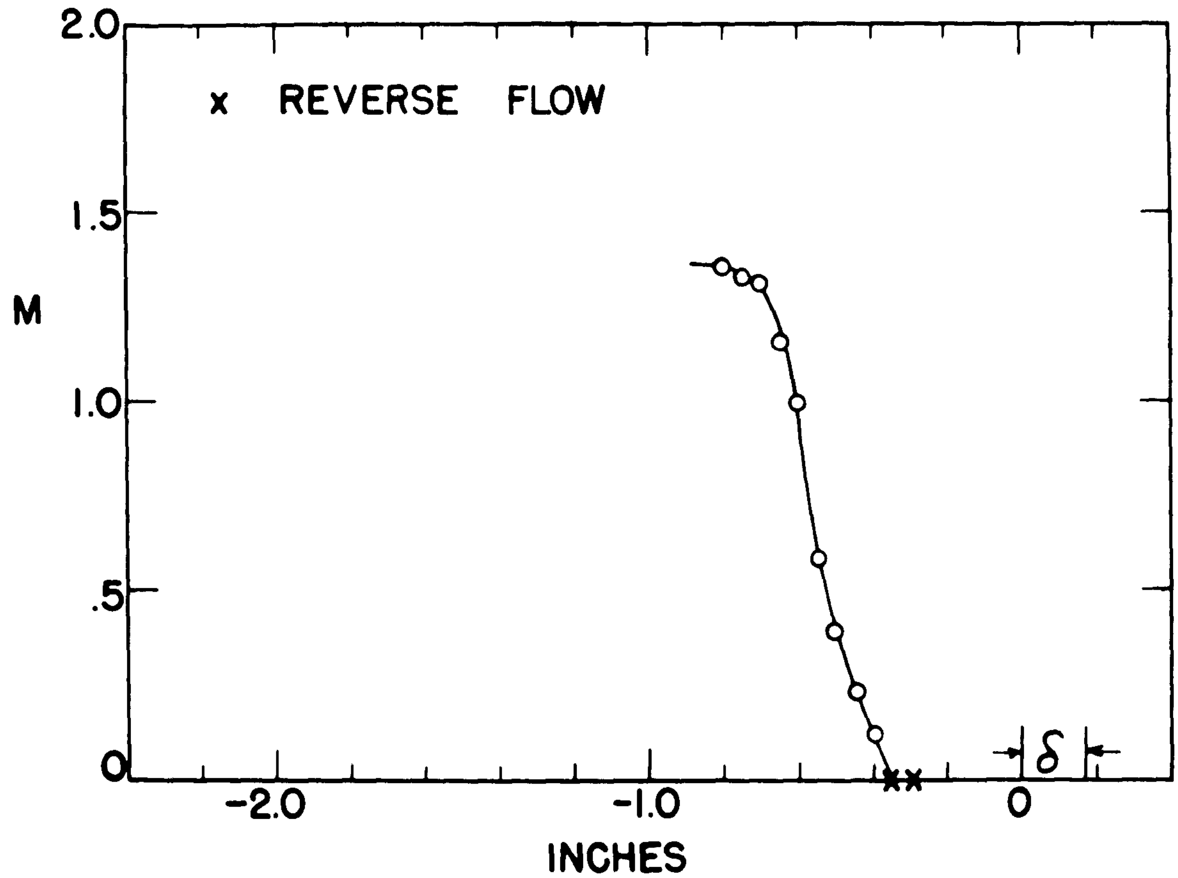


Figure 14 Mach Number Distribution .010" From Wall for .10" Step

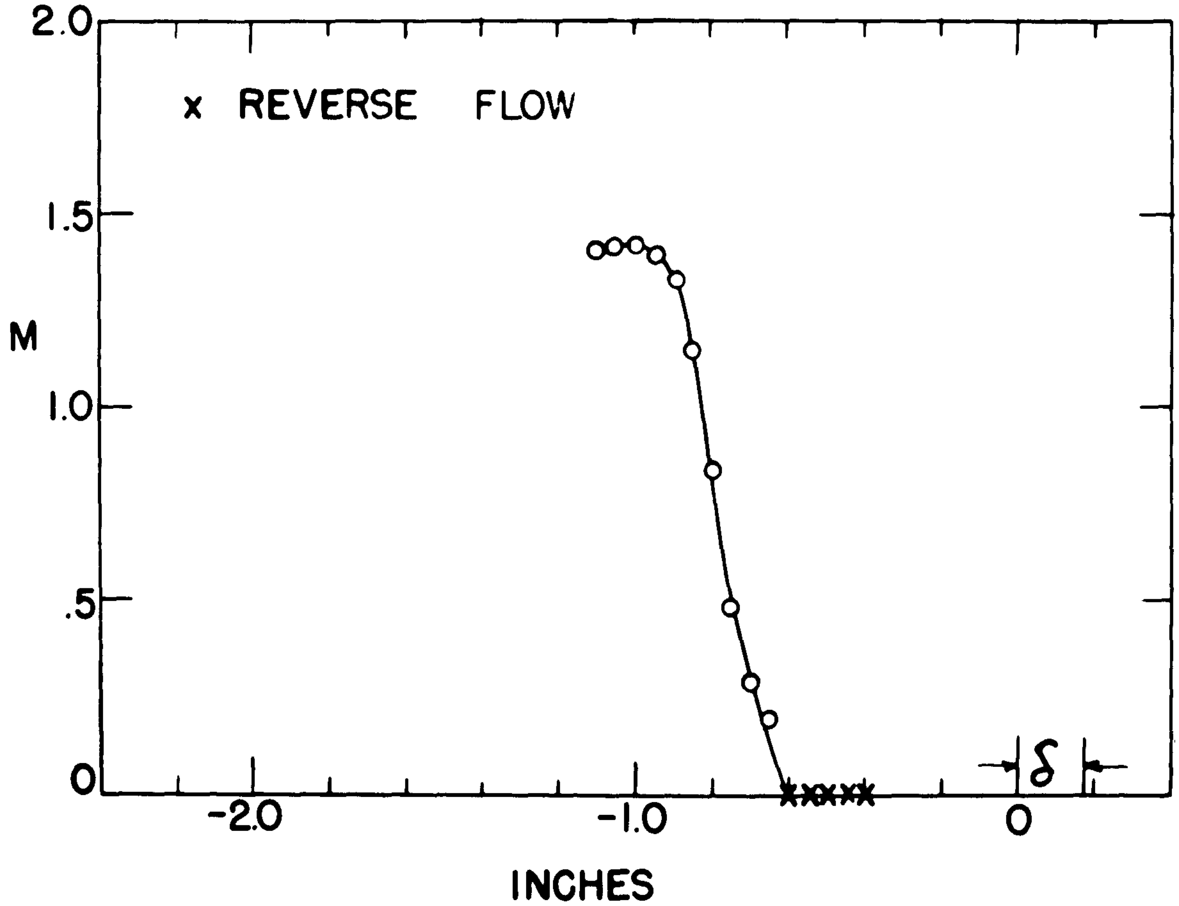


Figure 15 Mach Number Distribution .010" From Wall for .15" Step

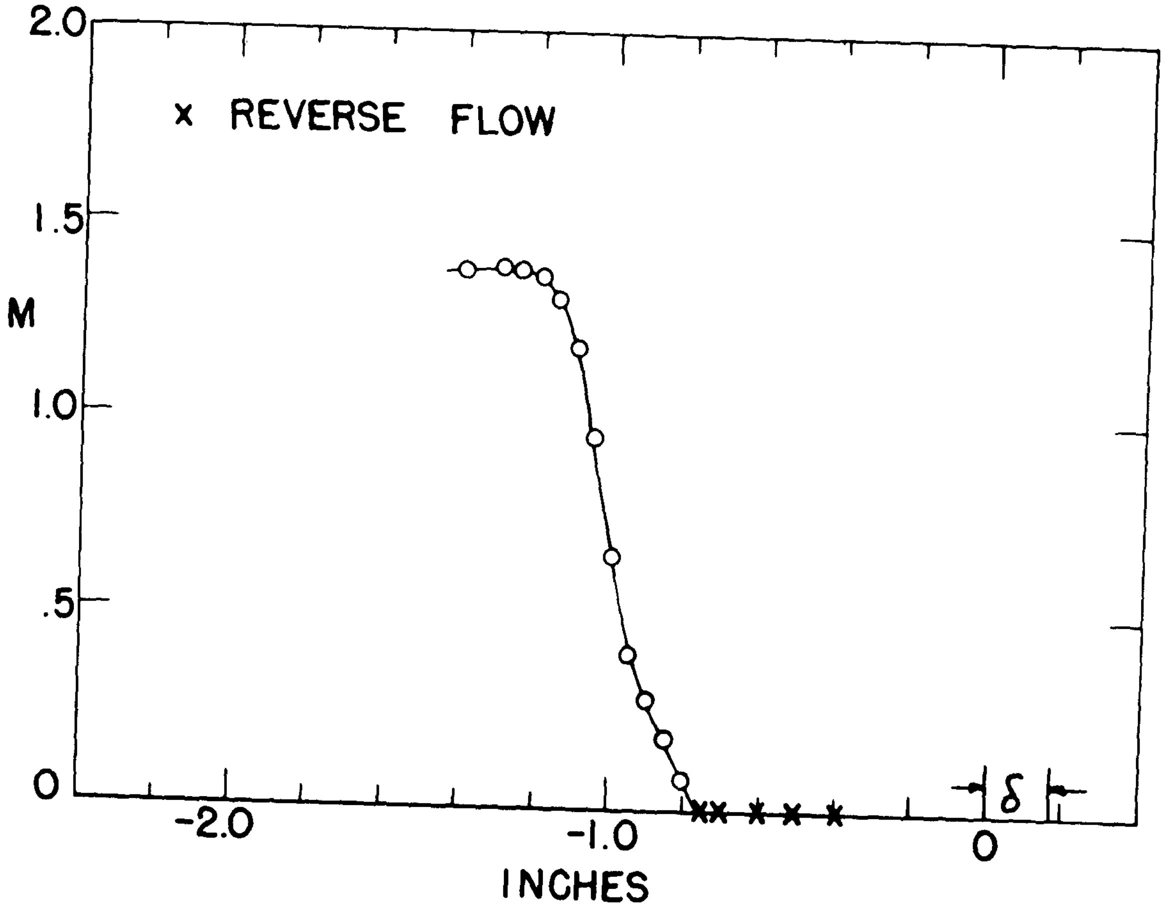


Figure 16 Mach Number Distribution .010" From Wall for .20" Step

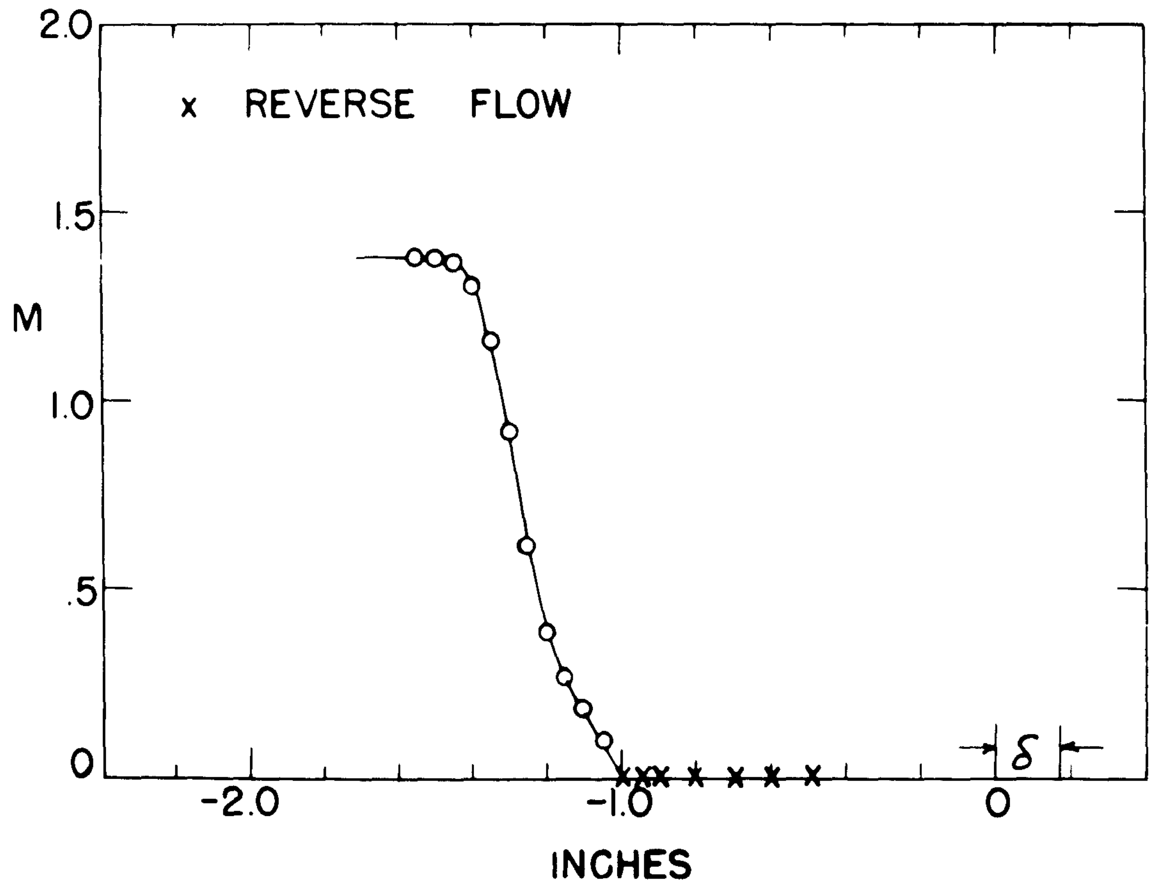


Figure 17 Mach Number Distribution .010" From Wall for .25" Step

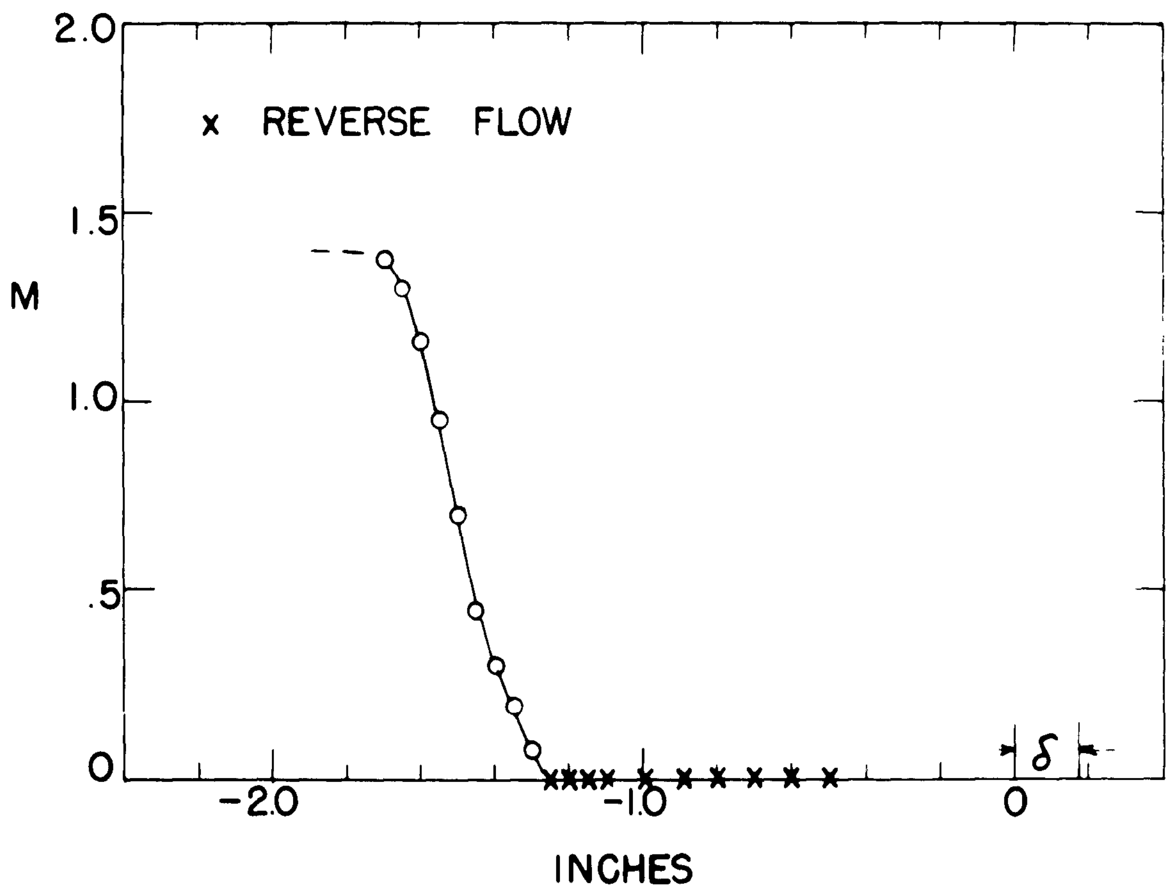


Figure 18 Mach Number Distribution .010" From Wall for .30" Step

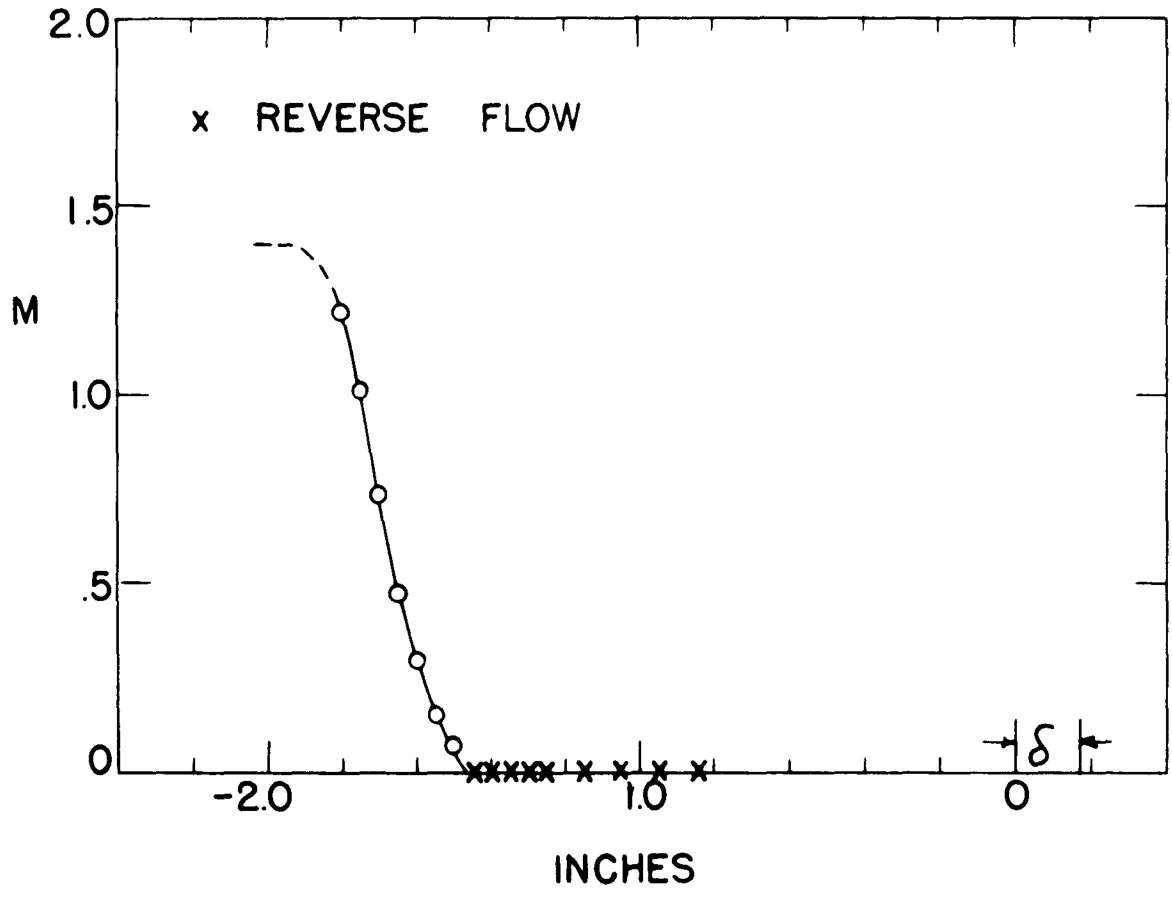


Figure 19 Mach Number Distribution .010" From Wall for .35" Step

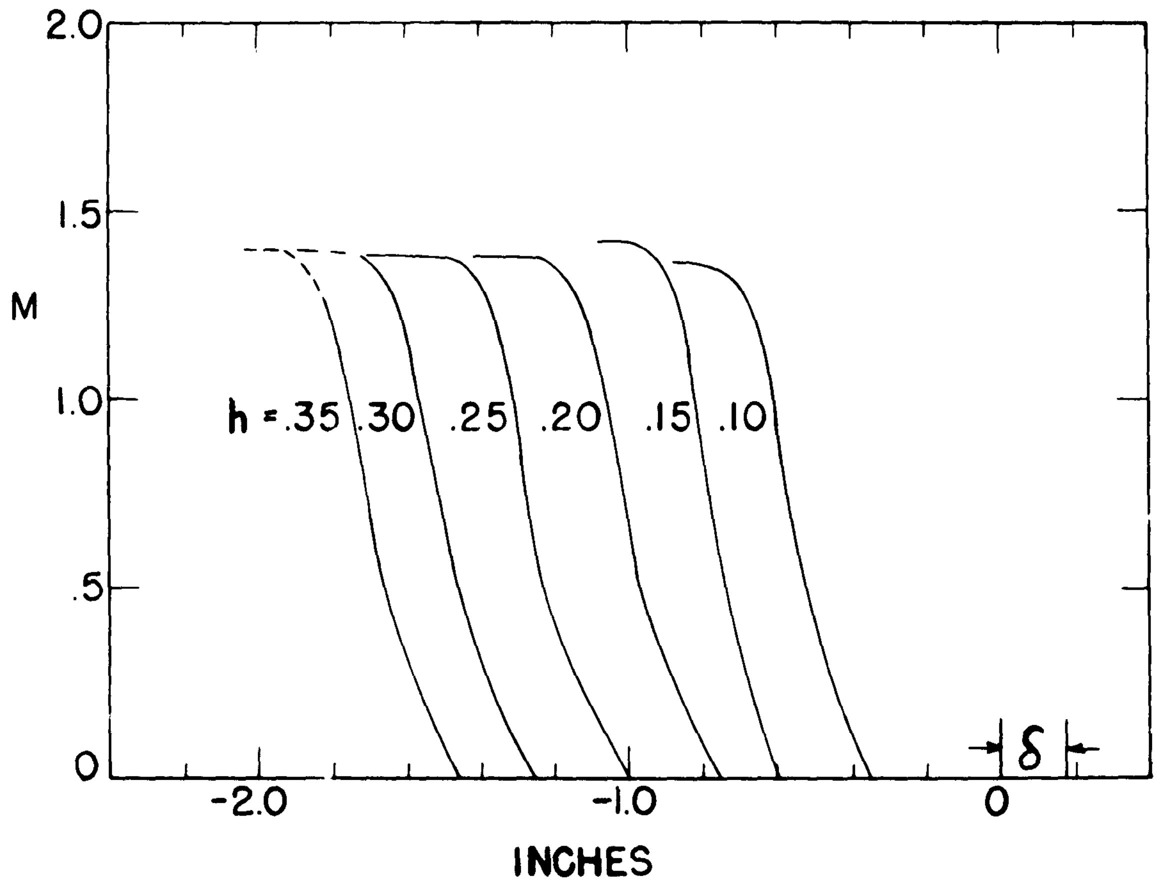


Figure 20 Composite of Mach Number Distribution .010" From Wall

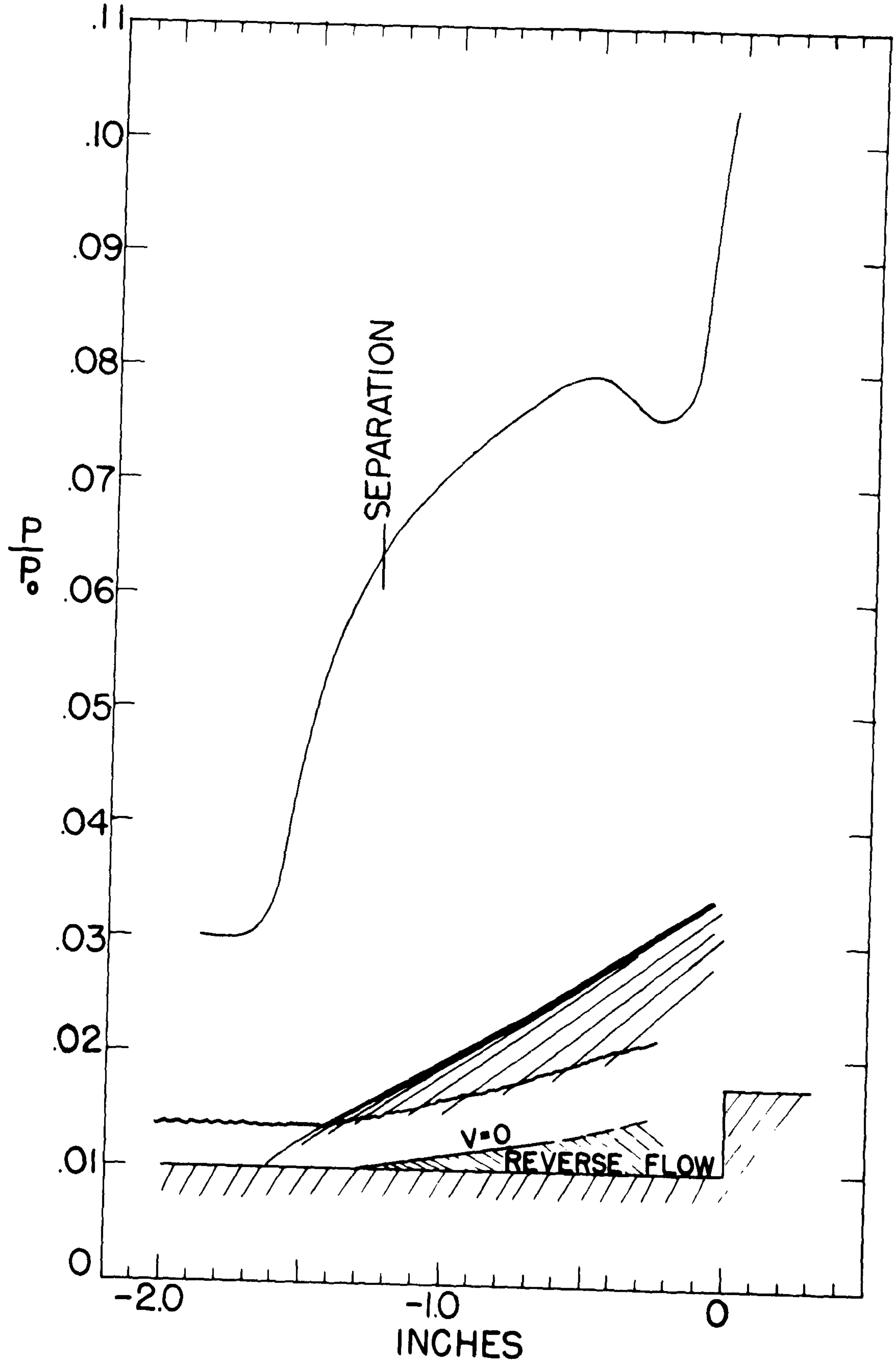


Figure 21 Schematic Drawing of Interaction For .30" Step in Juxtaposition With the Wall Static Pressure Distribution

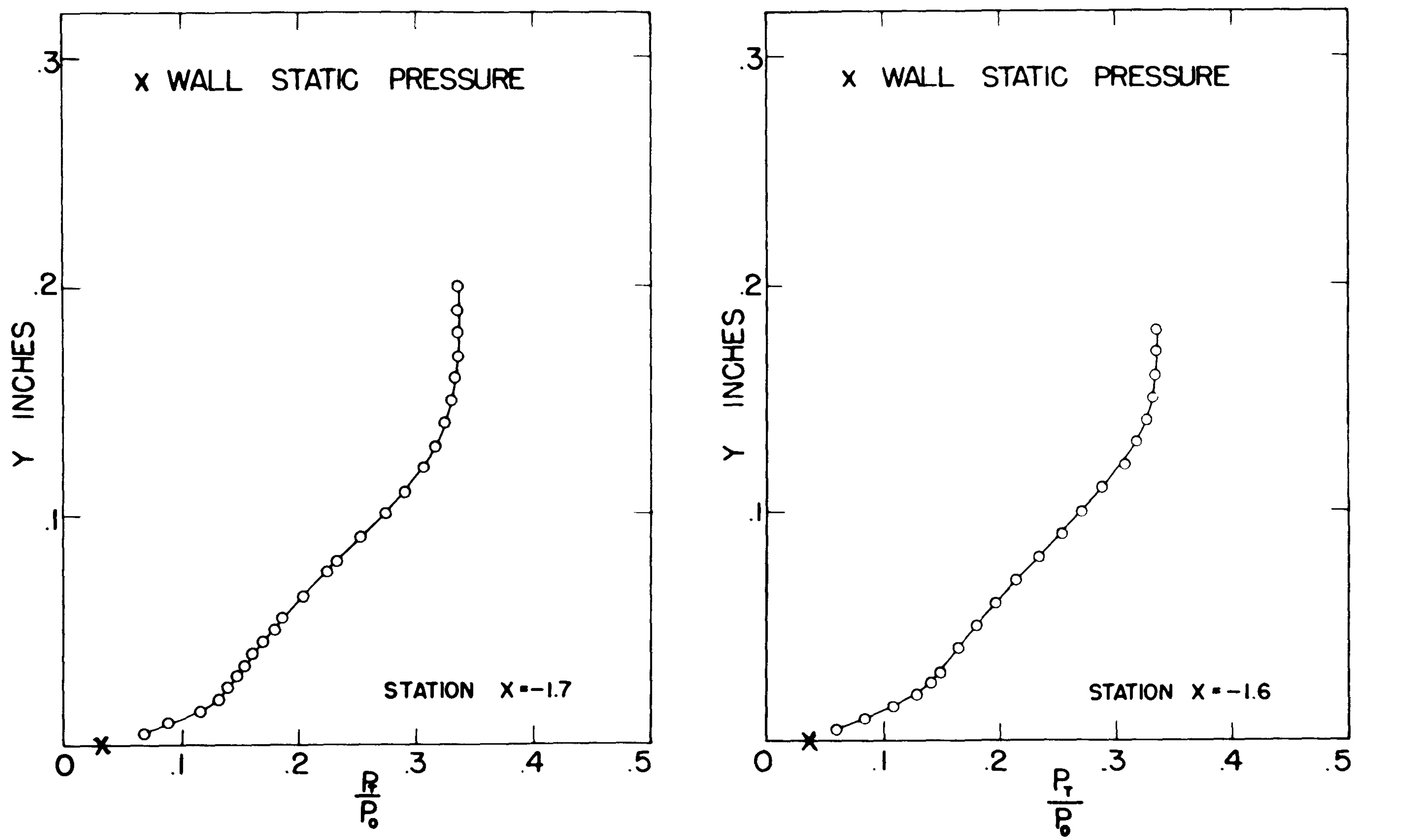
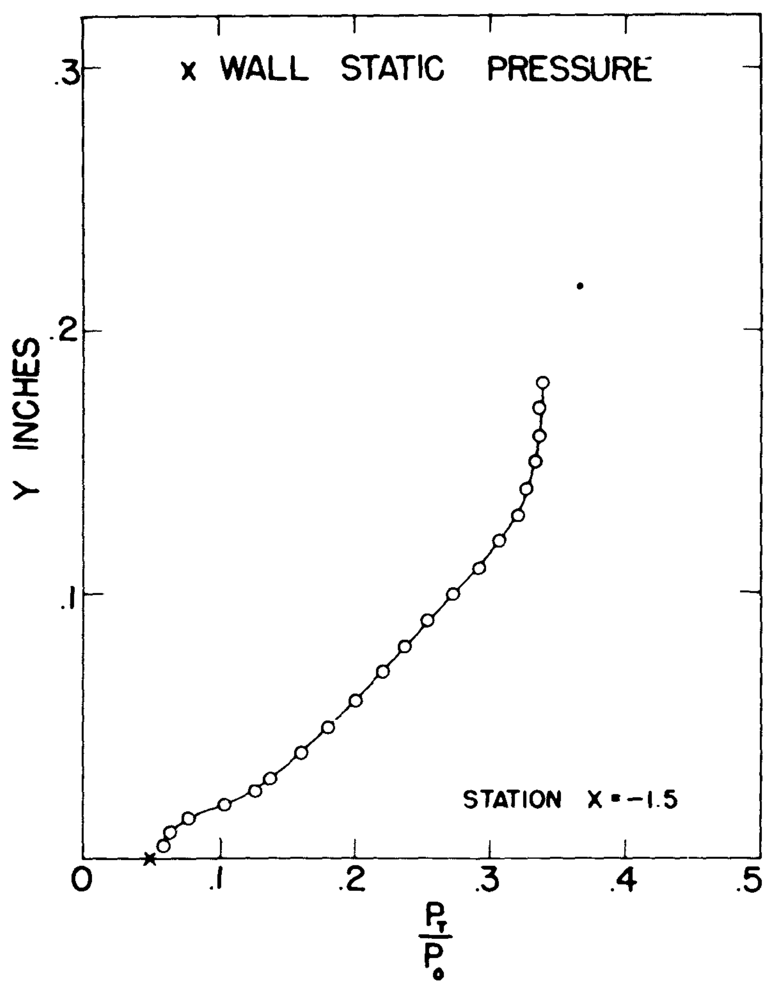


Figure 22 Total Head Profiles Through the Boundary Layer at Various Stations For .30" Step



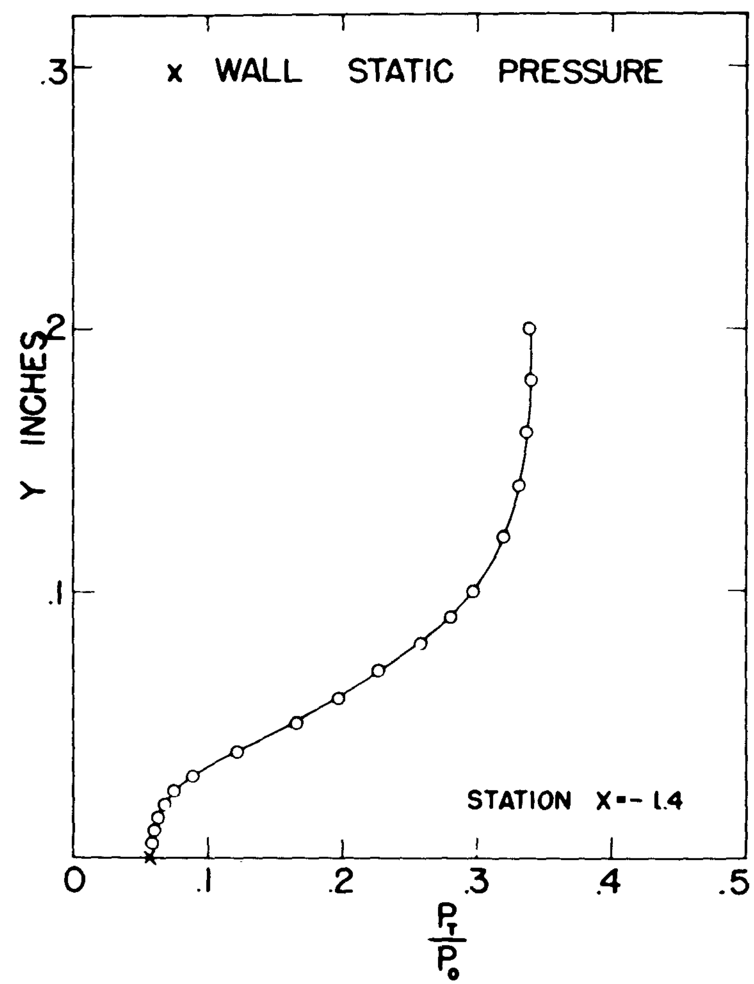


Figure 22 Continued

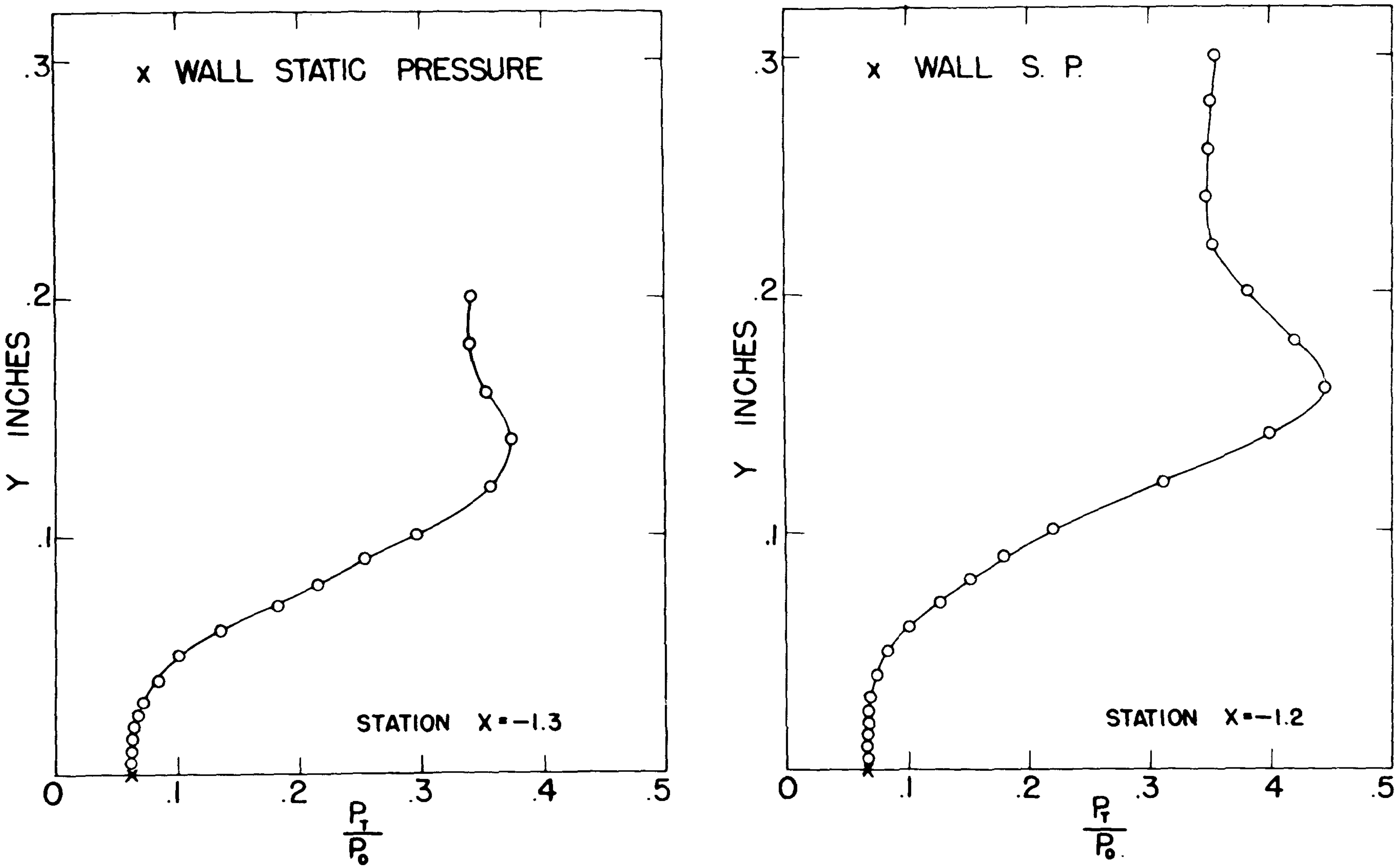


Figure 22 Continued

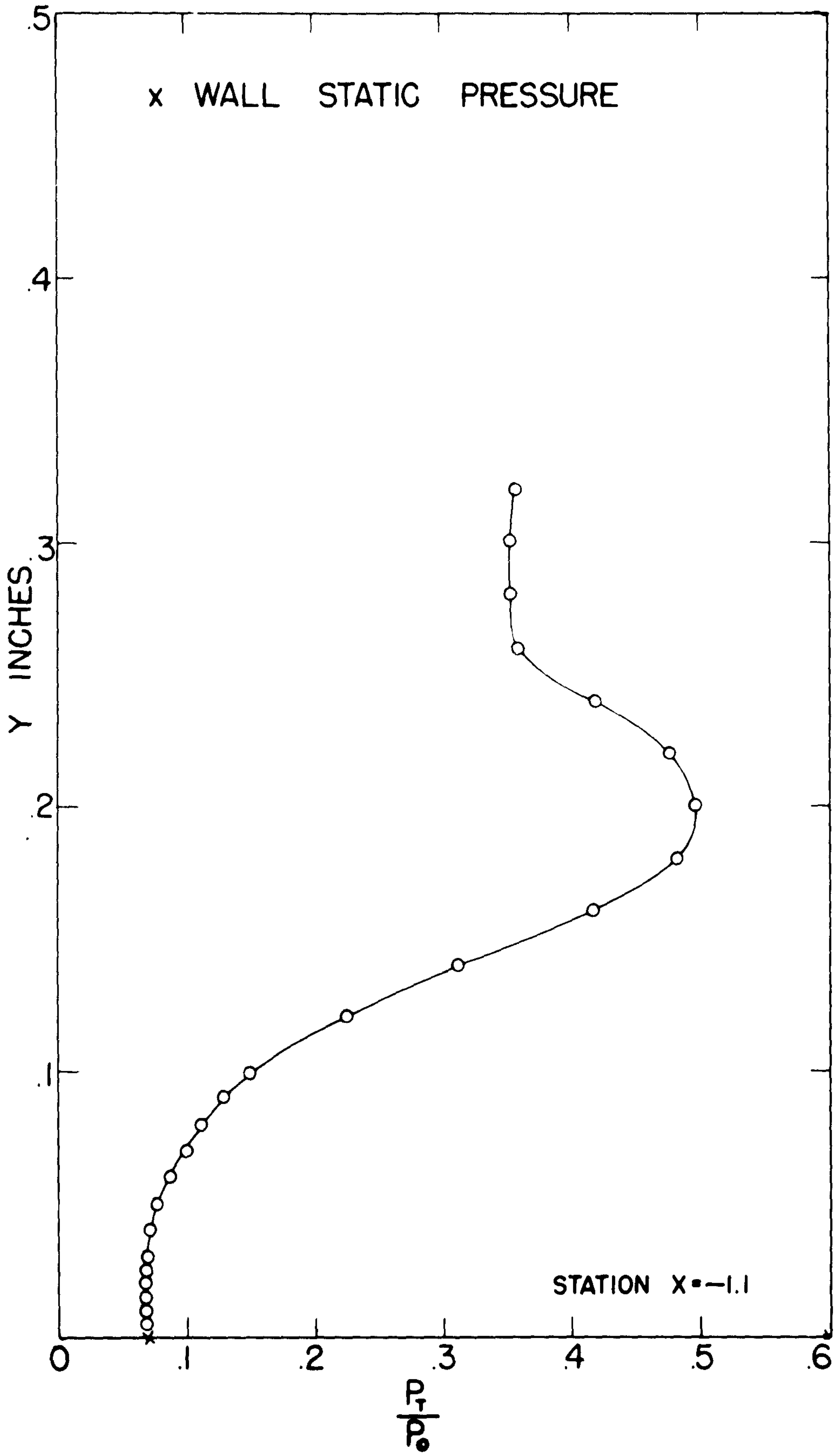


Figure 22 Continued

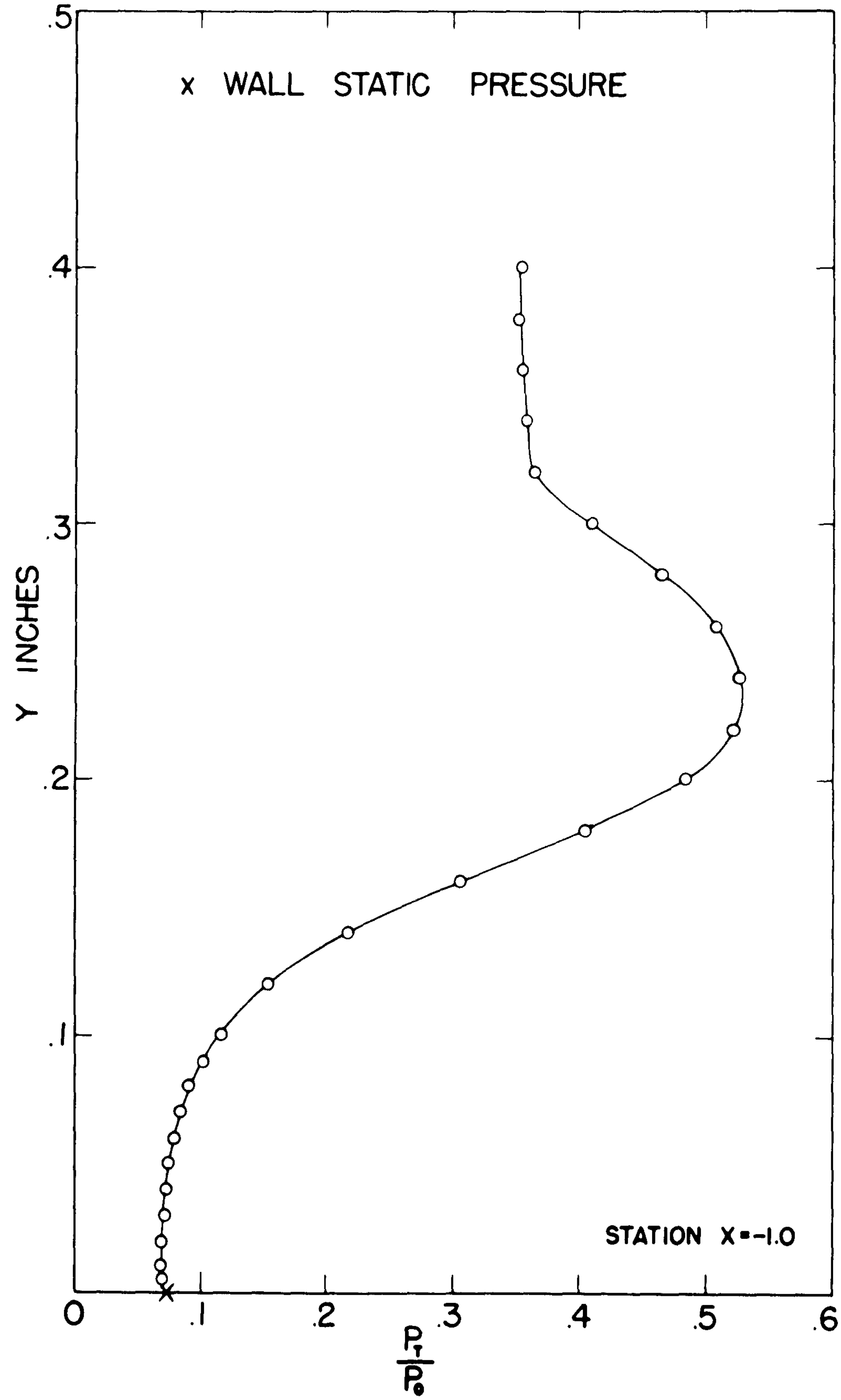


Figure 22 Continued

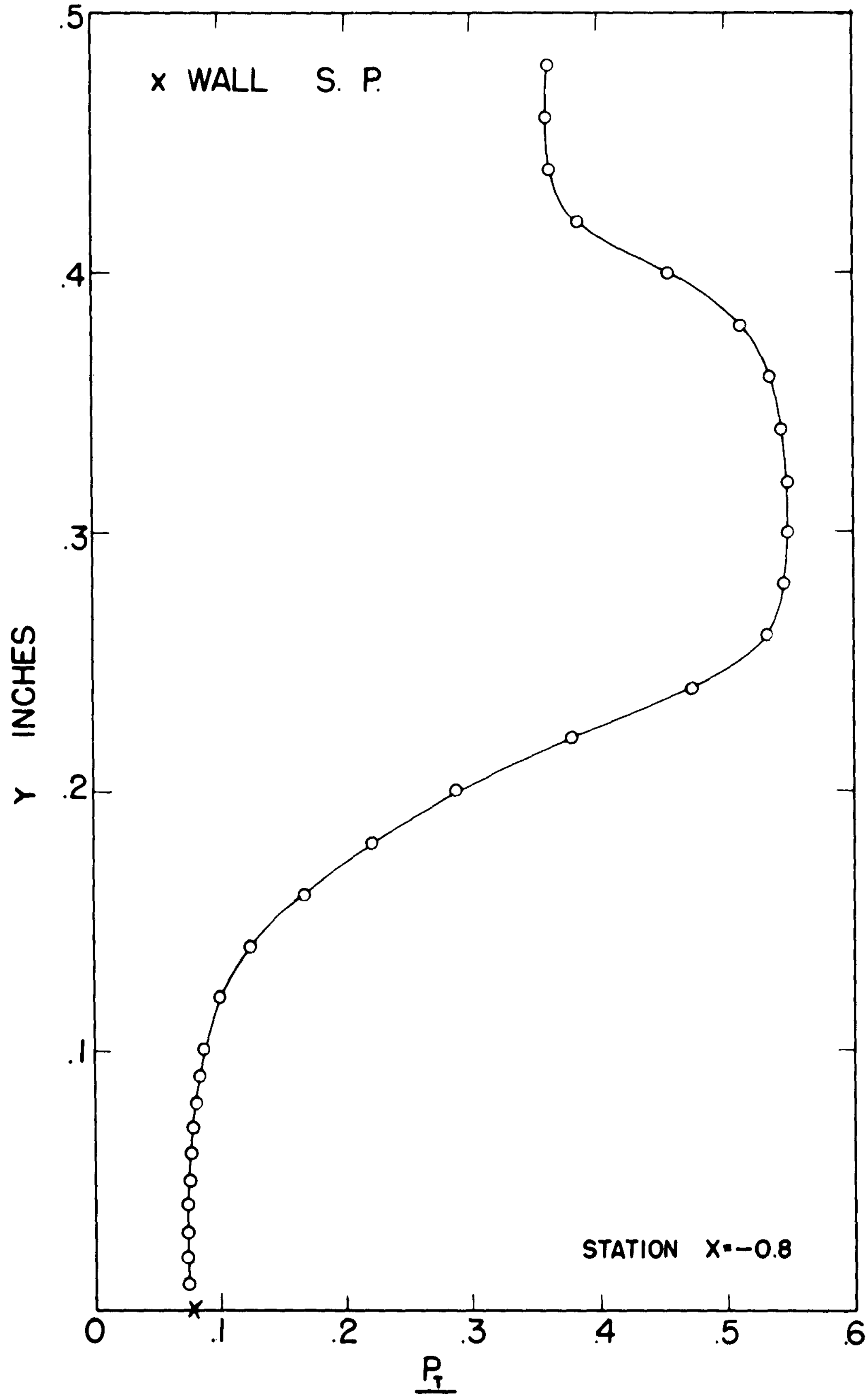


Figure 22 Continued

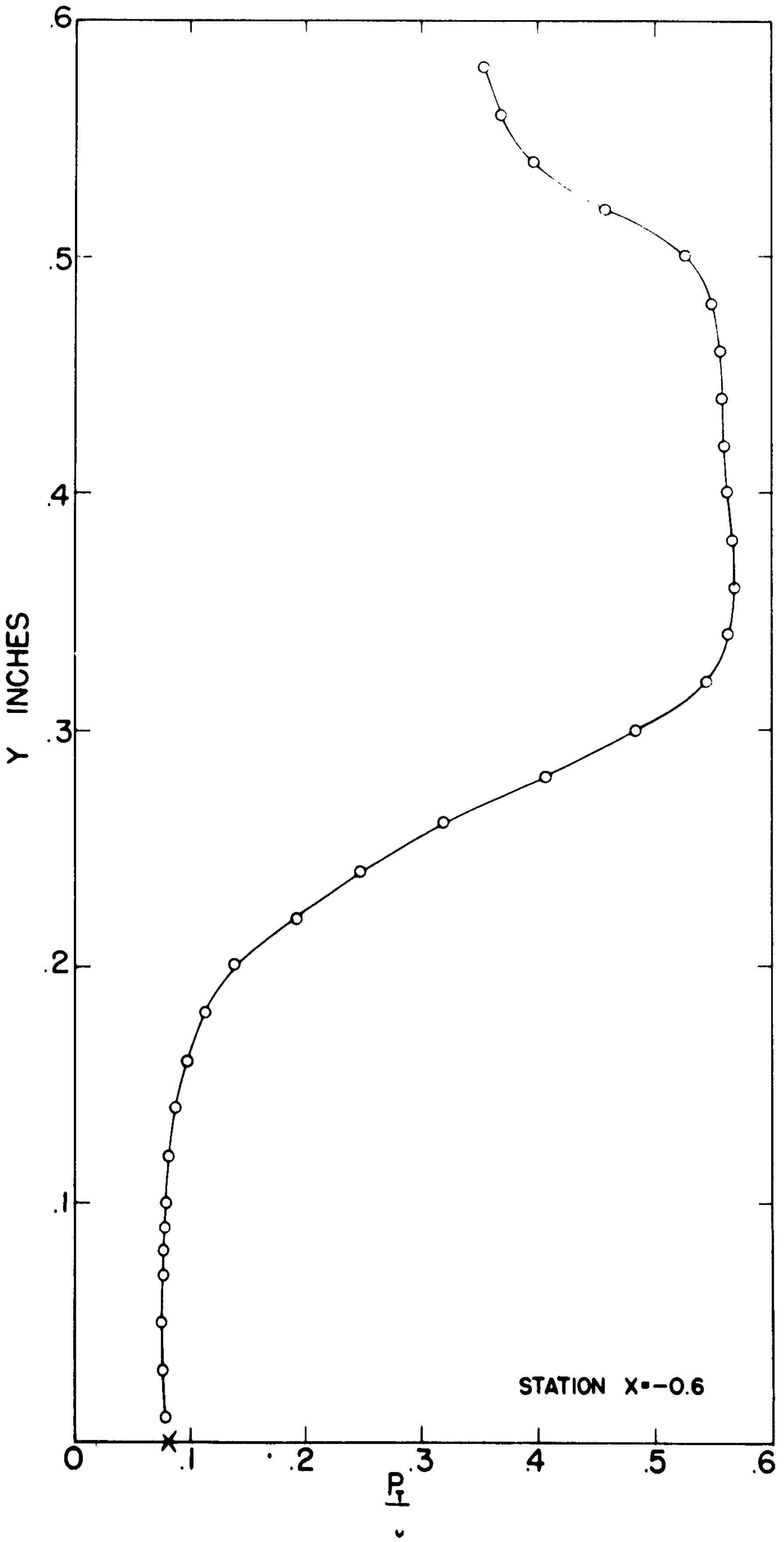
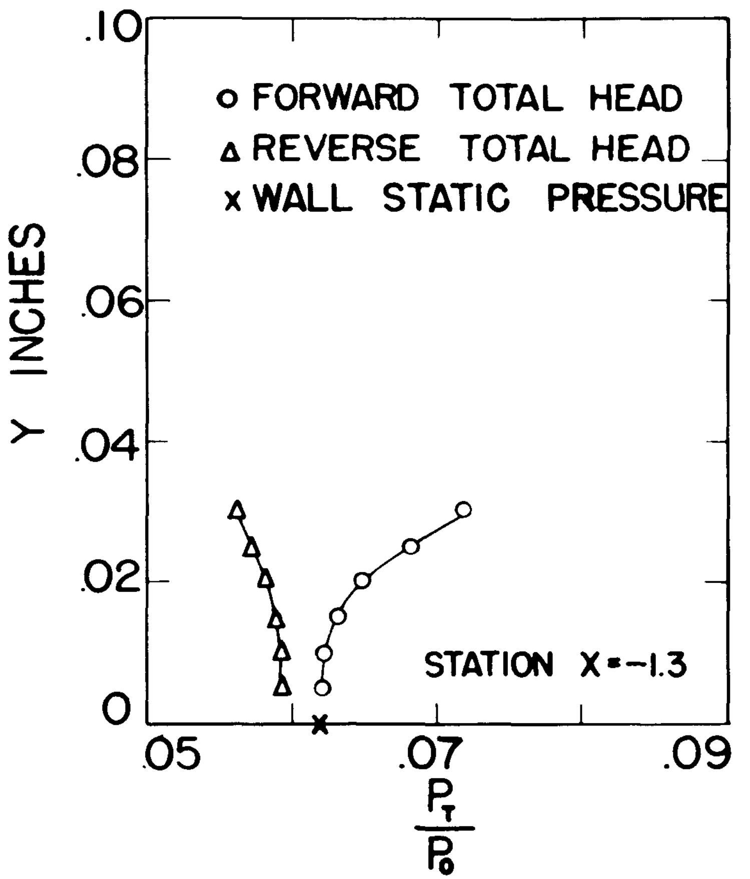


Figure 22 Concluded



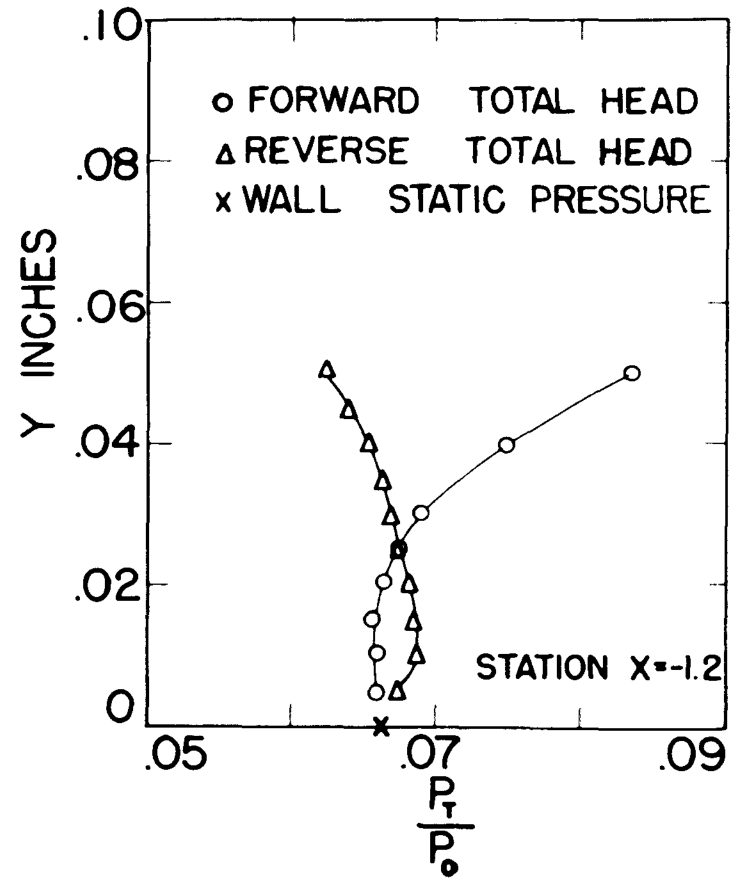


Figure 23 Total Head Surveys Through Separated Regions at Various Stations for .30" Step

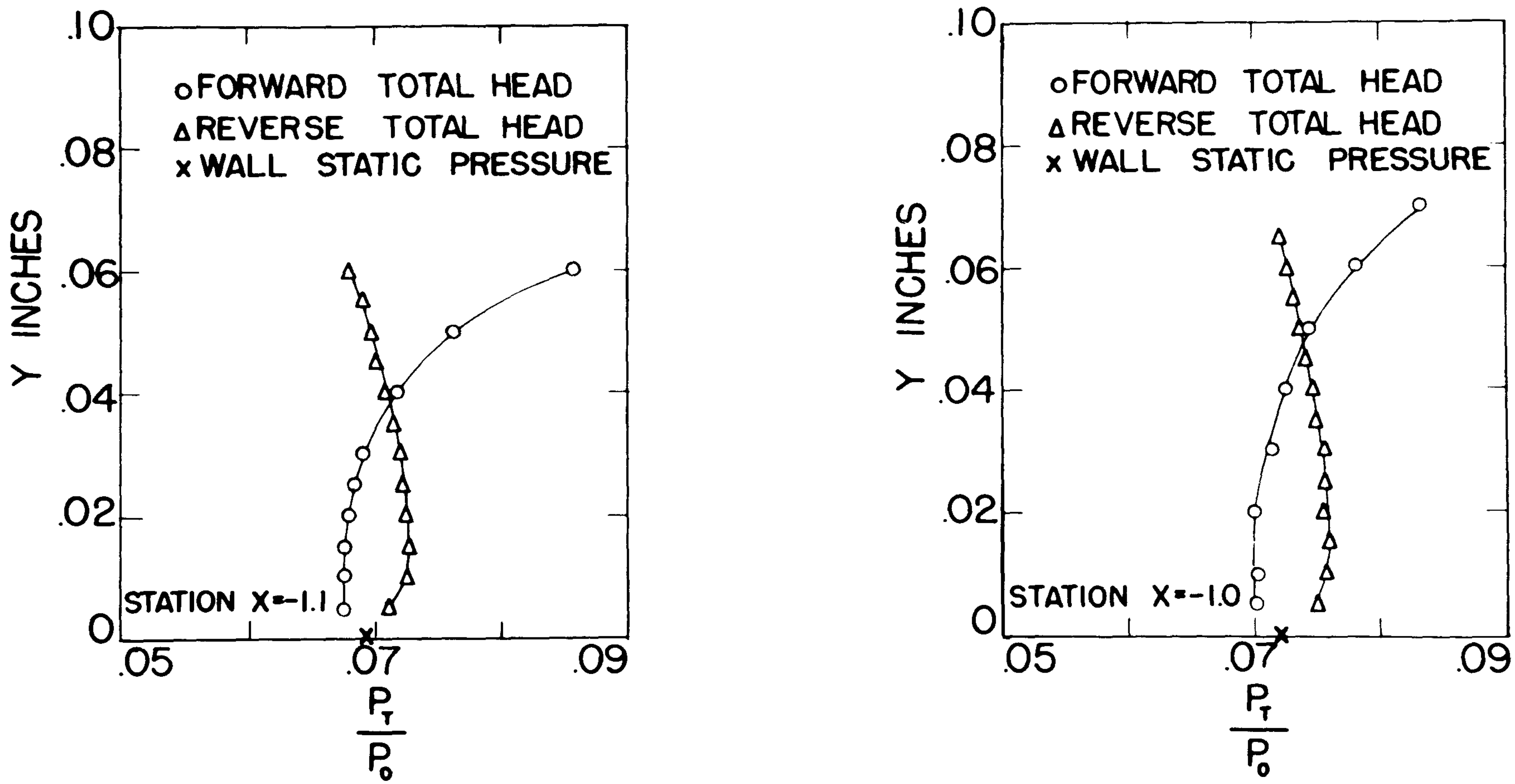


Figure 23 Continued

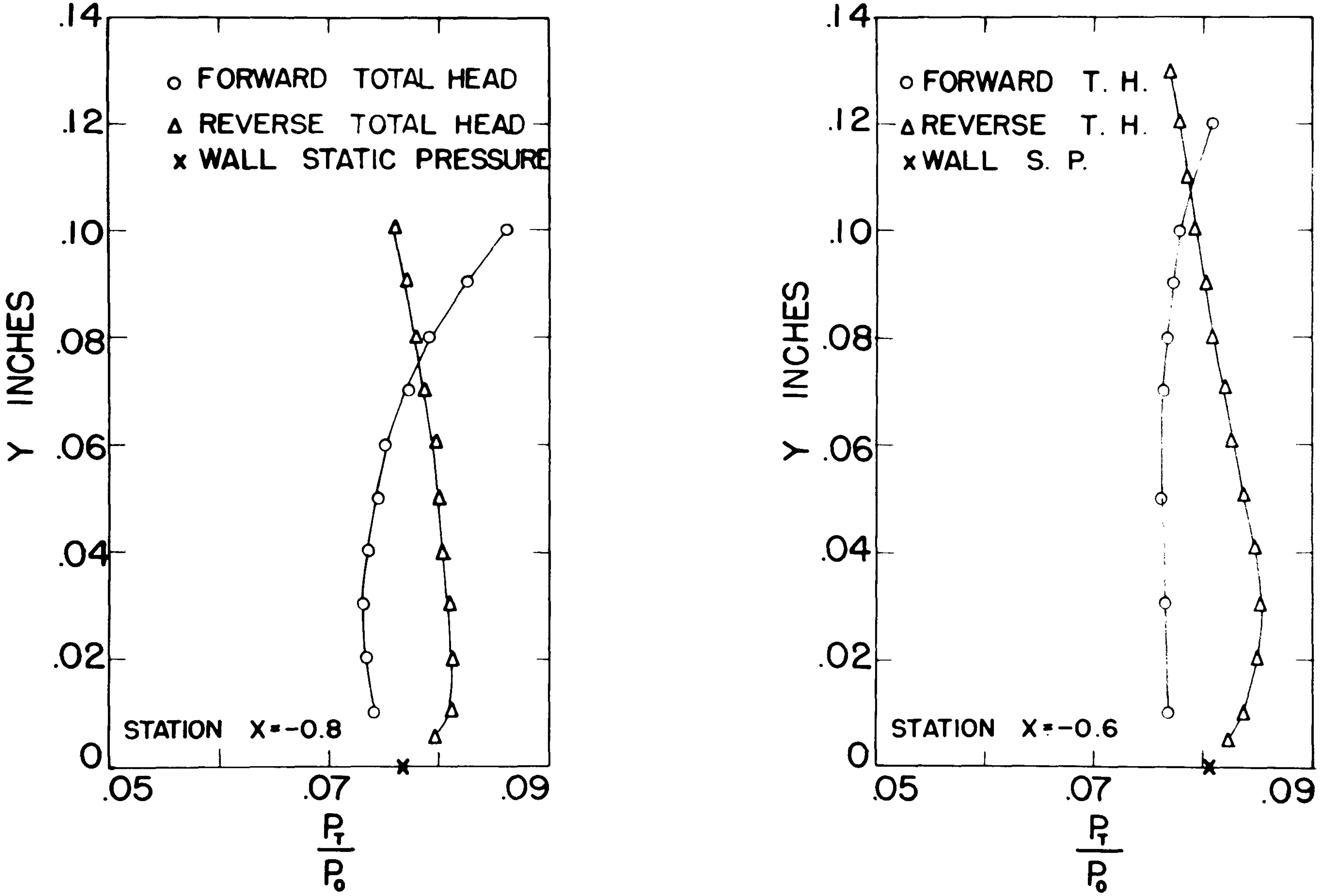


Figure 23 Concluded

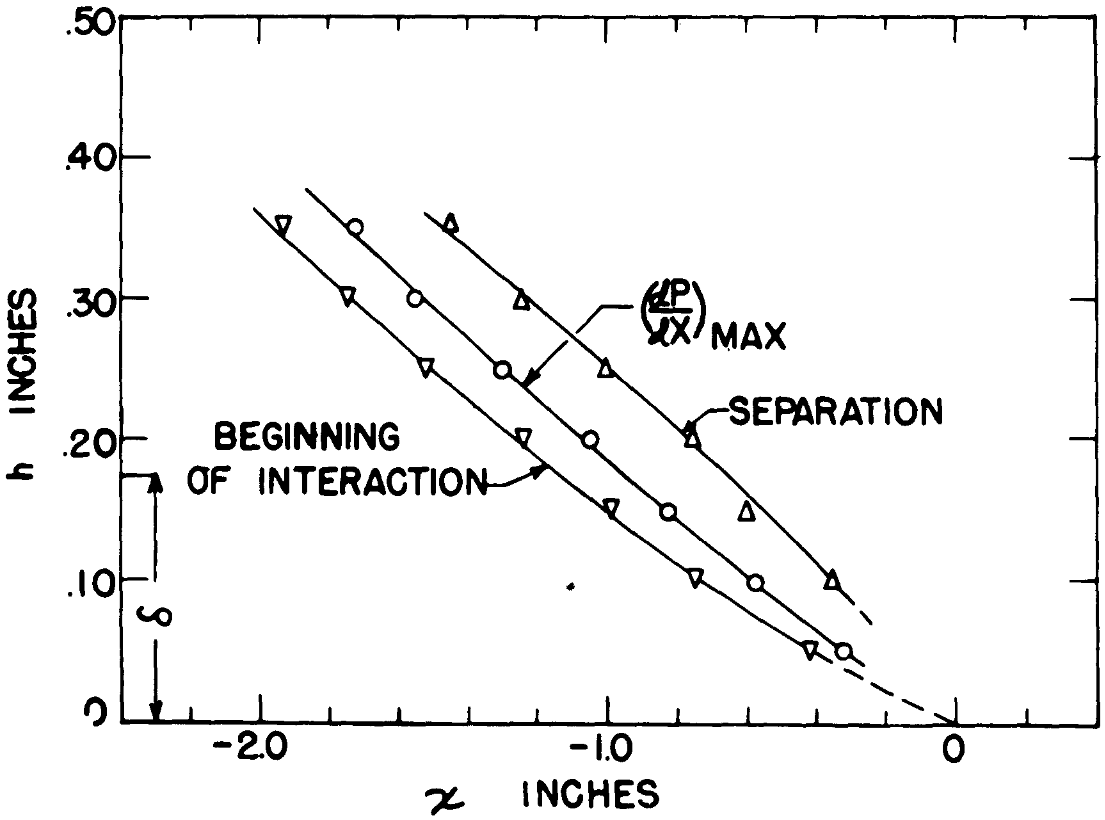


Figure 24 Interaction Regions for Various Step Heights

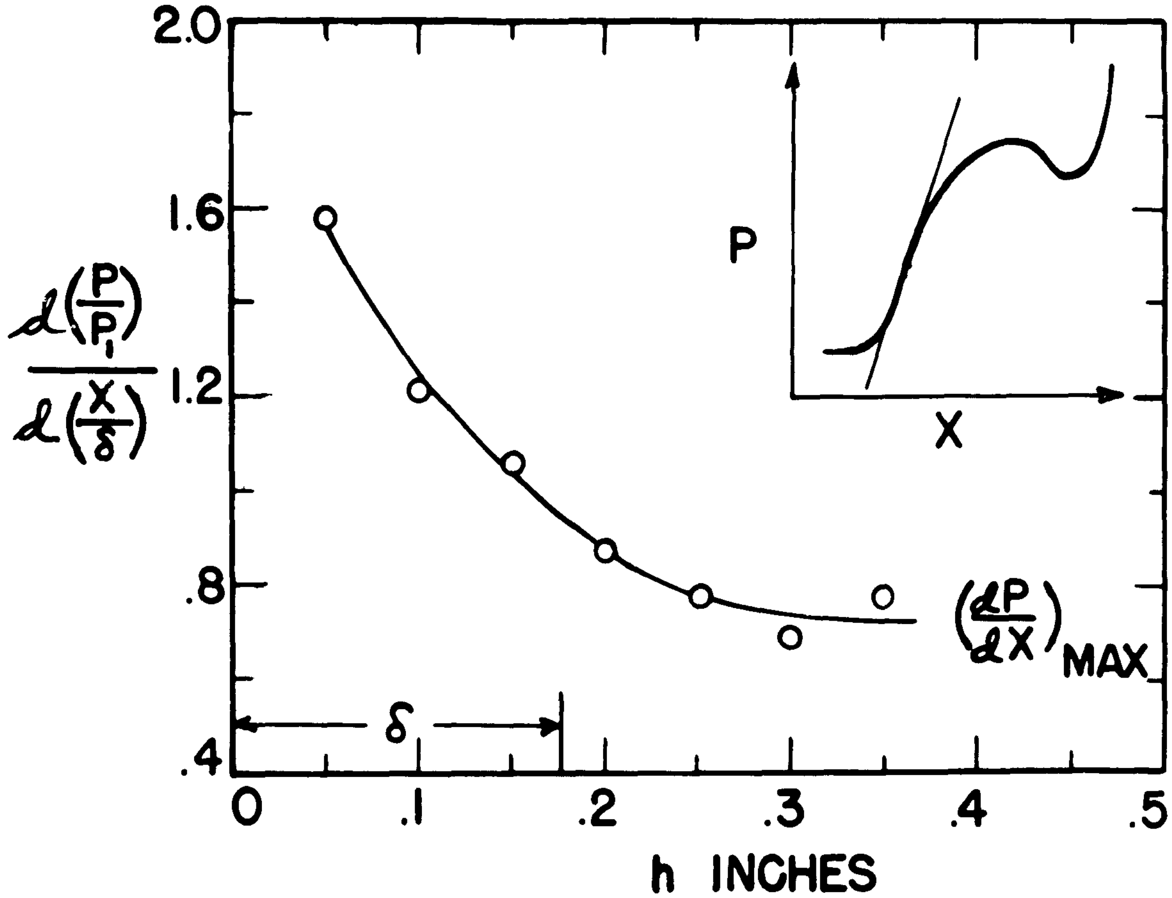


Figure 25 Maximum Wall Pressure Gradients for Various Step Heights

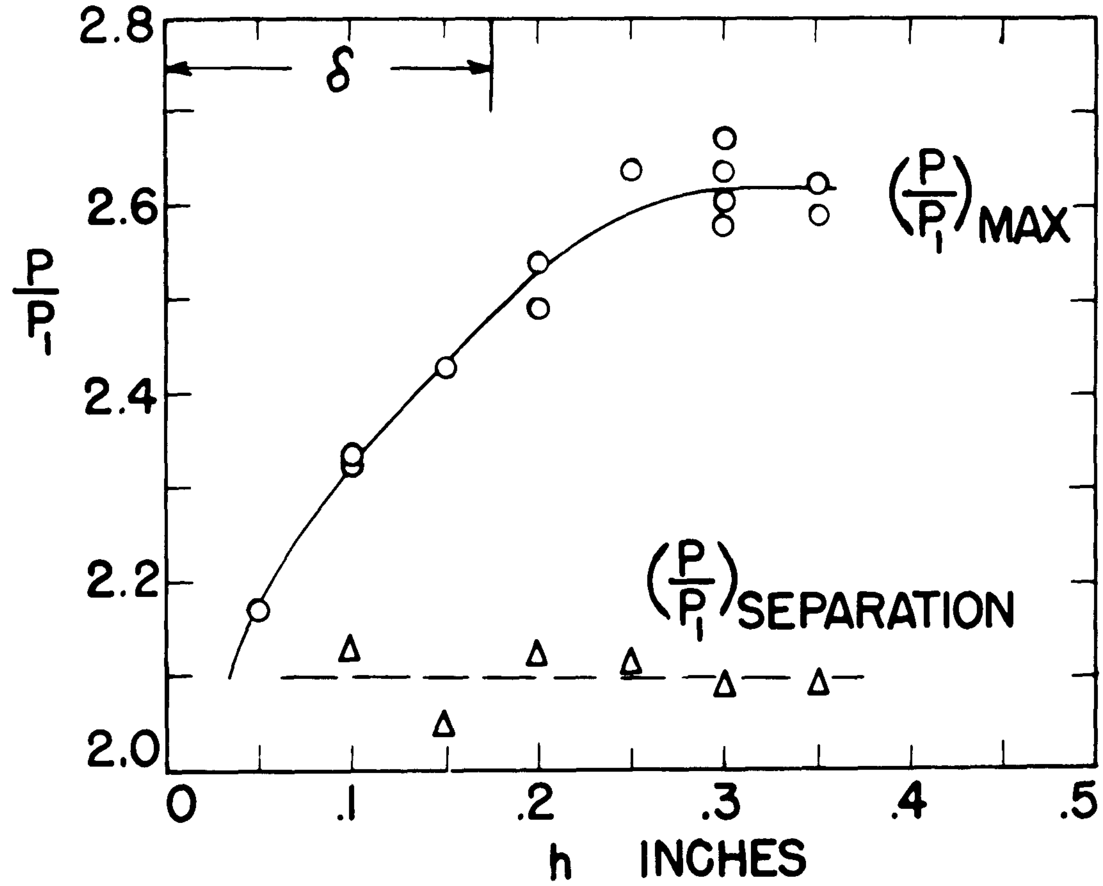


Figure 26 Pressure Ratio at Separation and the Maximum Pressure for Various Step Heights

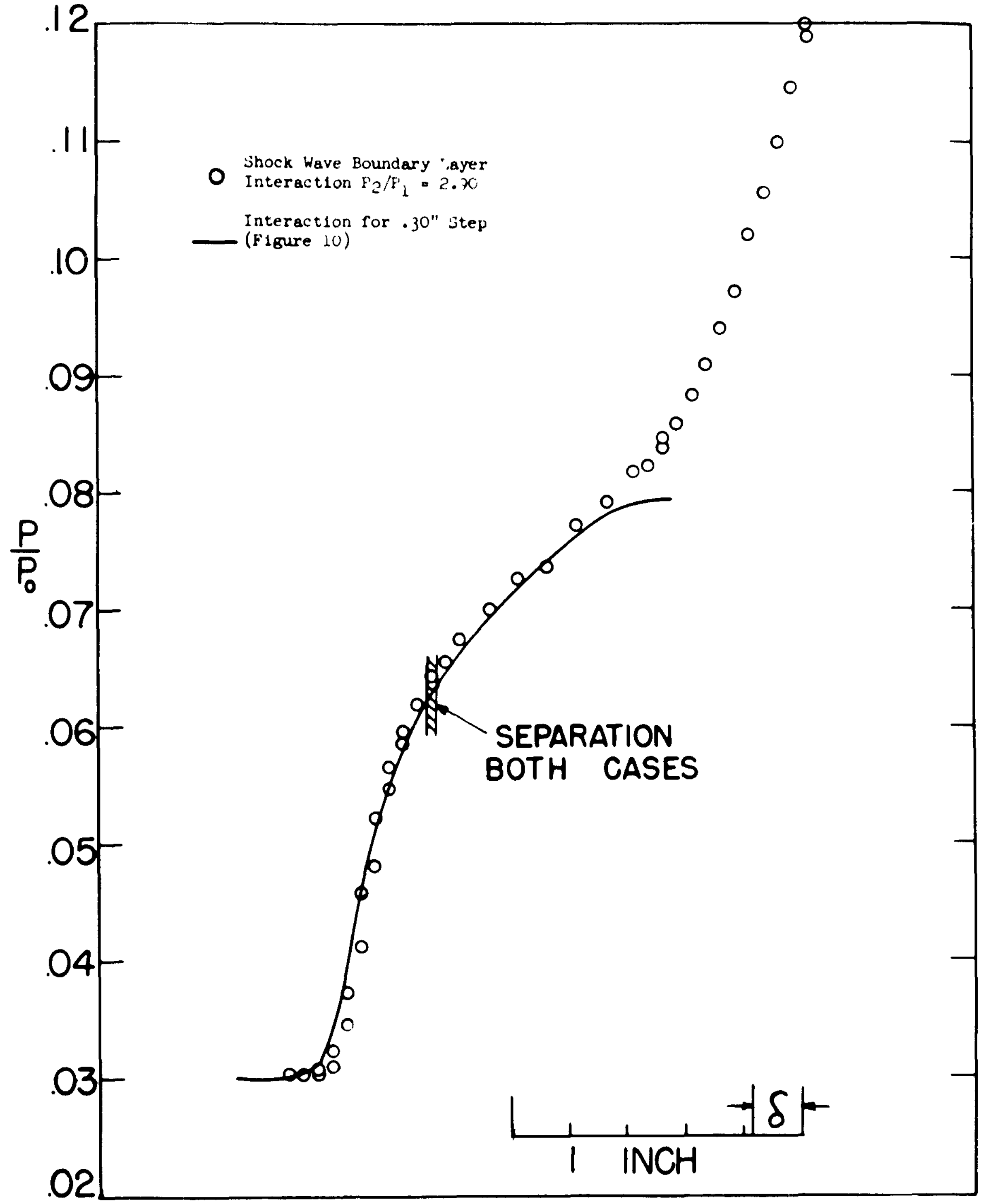


Figure 27 Comparison of the Wall Static Pressure Curves for Shock Wave Boundary Layer Interaction and Step Studies